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ON THE DEVELOPMENT OF HYDRAULIC ENGINEERING GUIDELINES FOR FISH-FRIENDLY STANDARD BOX CULVERTS, WITH A FOCUS ON SMALL-BODY FISH

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On the Development of Hydraulic Engineering Guidelines for Fish-Friendly Standard Box Culverts, with a Focus on Small-Body Fish

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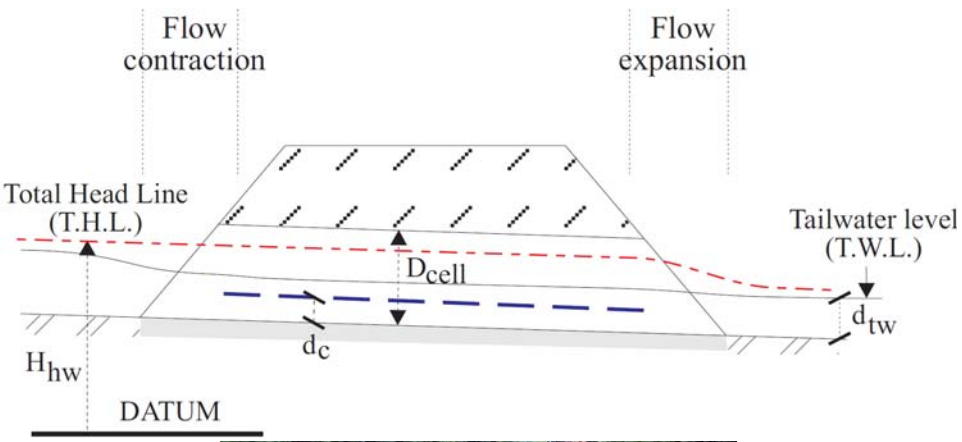

Standard box culvert operation for less-than-design flow: schematic (top) and outlet flow (bottom)

ABSTRACT

A culvert is a covered channel installed to pass water through an embankment. It is a hydraulic structure, and its environmental impact in terms of stream connectivity and fish passage may affect both upstream and downstream catchments. Guidelines were proposed to allow for upstream fish passage in culverts. Most are based upon a number of limited criteria, which too often increase substantially the total cost of the culvert structure. In this study, new design guidelines for fish-friendly box culverts are proposed, with a focus on the upstream passage of small-bodied fish, based upon recent scientific findings. The method proposes to optimise the culvert design in terms of fish passage for less-than-design flows and in terms of flood capacity for larger discharges. Low-velocity zones are provided in the form of a percentage of wetted flow area where $0 < V_x < U_{fish}$, where V_x is the local longitudinal velocity component and U_{fish} is a characteristic fish speed linked to swimming performances of targeted fish specie, herein small-bodied fish. The new approach is based upon the entire flow field in the barrel, specifically the longitudinal velocity map, rather than the bulk velocity, because small-body fish swim next to boundaries. The influence of the relative discharge threshold Q_1/Q_{des}, critical fish speed U_{fish} and percentage of flow area on the size and costs of box culverts was quantified based upon hydraulic engineering calculations, where Q_{des} is the design discharge and Q_1 is the threshold discharge below which the culvert is optimised in terms of fish passage. Compared to traditional hydraulic designs, the results showed a substantial increase in culvert size, and construction costs, for $U_{fish} < 0.3$ m/s and $Q_1/Q_{des} > 0.3$ to deliver 15% flow area with $0 < V_x < U_{fish}$, in smooth box culverts. Further detailed CFD calculations for recessed cell showed similar trends as those for a culvert barrel invert at natural ground level, albeit with a significantly more complicated hydrodynamic field in the barrel.

Keywords: Standard box culverts, Upstream fish passage, Design guidelines, Small-body fish; Low-velocity zone, Smooth barrel.

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LIST OF SYMBOLS

The following symbols are used in this report:

A	channel cross-section area (m^2);
B	channel width (m);
B_{cell}	internal width (m) of culvert barrel cell;
B_{min}	minimum total internal barrel width (m);
$C_{Chézy}$	Chézy friction coefficient ($m^{1/2}.s$);
D_{cell}	internal height (m) of culvert barrel cell;
D_H	hydraulic diameter (m): $D_H = 4 \times A/P_w$;
d	water depth (m);
d_c	critical flow depth (m); for a rectangular channel: $d_c = \sqrt[3]{\frac{q^2}{g}}$
d_{tw}	tailwater water depth (m);
E	specific energy (m): $E = H - z_o$;
f	Darcy-Weisbach friction factor;
g	gravity acceleration (m/s^2); in Brisbane, $g = 9.794\ m/s^2$;
H	total head (m);
h	afflux (m);
h_{max}	maximum acceptable afflux (m);
K_{out}	exit loss coefficient;
k_e	entrance loss coefficient;
k_s	equivalent sand roughness height (m);
L_{barrel}	barrel length (m);
L_{culv}	entire culvert length (m);
N_{cell}	number of (identical) culvert barrel cells;
$(N_{cell})_{des}$	number of culvert barrel cells for optimum hydraulic engineering design (i.e. flood capacity only);
n_{GM}	Gauckler-Manning coefficient ($s/m^{1/3}$);
P_w	wetted perimeter (m);
Q	water discharge (m^3/s);
Q_{cell}	water discharge (m^3/s) per barrel cell;
Q_{des}	design discharge (m^3/s);
Q_{min}	minimum discharge (m^3/s) for fish passage;
Q_1	threshold discharge (m^3/s);
Q_{30}	flow rate (m^3/s) occurring no more than 30 days per year;
Q_{330}	flow rate (m^3/s) occurring no more than 330 days per year;
q	water discharge per unit width (m^2/s), or unit discharge;
S_f	friction slope;

S_o	bed slope: $S_o = \sin\theta$;
$T_{50\%}$	storm event period (s) during which the relative water level is larger than 50% of the maximum water elevation relative to the base flow level;
U_{fish}	characteristic fish speed (m/s);
V	flow velocity (m/s);
V_{mean}	cross-sectional averaged velocity (m/s), also called bulk velocity;
$(V_{mean})_{des}$	design bulk velocity (m/s) in culvert barrel;
V_x	local longitudinal velocity component (m/s) positive downstream;
x	longitudinal distance (m) positive downstream;
y	transverse distance (m) positive towards the left sidewall;
z	vertical elevation (m) positive upwards;
z_o	bed elevation (m);
ΔH	total head loss (m);
μ	water dynamic viscosity (Pa.s);
θ	angle between bed and horizontal;
ρ	water density (kg/m^3);

Subscript

barrel	barrel flow conditions;
des	design flow conditions;
entry	barrel entry flow conditions;
exit	barrel exit flow conditions;
hw	headwater conditions (i.e. upstream flood plain conditions);
in	inlet downstream end's flow conditions;
tw	tailwater conditions (i.e. downstream flood plain conditions);
x	longitudinal direction;

Superscript

ic	inlet control conditions;
oc	outlet control conditions;

Abbreviations

AEP	average recurrence interval;
ARI	annual exceedance probability;
ARR	Australian rainfall and runoff
CFD	computational fluid dynamics;
LVZ	low-velocity zone;
T.H.L.	total head line;
T.W.L.	tailwater level;

2D	two-dimensional;
3D	three-dimensional.

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1. INTRODUCTION

A culvert is a covered channel designed to pass flood waters, drainage flows, natural streams through earthfill and rockfill structures, e.g. roadway, railroad. The design can vary from a simple geometry (standard box culvert) to a hydraulically-smooth shape (M.E.L. culvert) (APELT 1983, CHANSON 1999,2000). A culvert consists of three components: the intake or inlet, the barrel or throat, and the diffuser or outlet (Fig. 1-1). The cross-sectional shape of the barrel may be circular (pipe) or rectangular (box and multi-cell box); a culvert may be designed as a single cell or multiple cell structure (Fig. 1-2). Figure 1-2 presents typical multicell standard box culverts in eastern Australia.

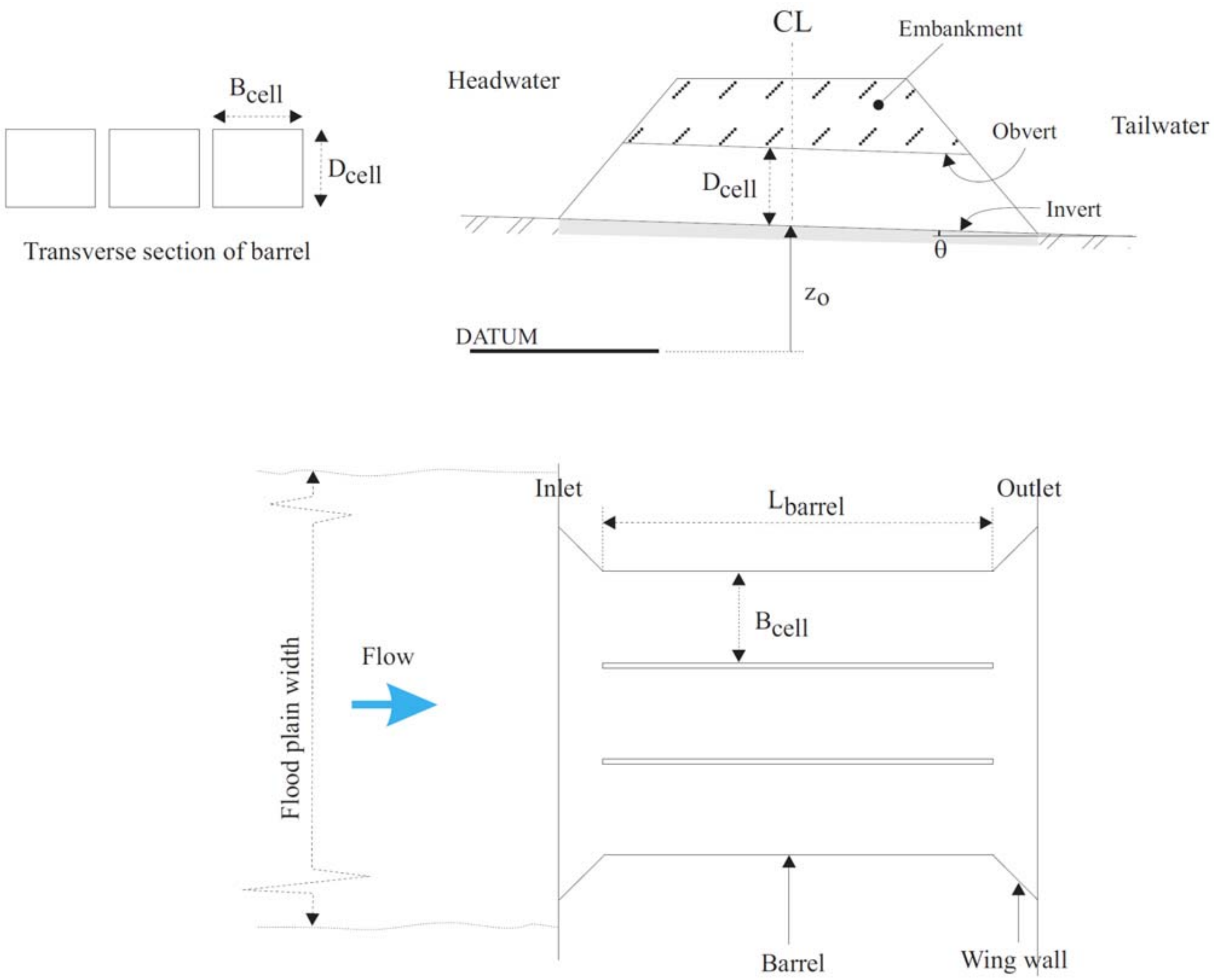

Fig. 1-1 - Definition sketch of a standard multicell box culvert with invert placed on natural ground level

(A) Multicell box culvert beneath the Warrego Highway in Dalby QLD on 6 April 2018

(B) Inlet (Left) and outlet (Right) of multicell box culvert on Whitton Creek beneath Whitton Road, Indooroopilly QLD on 24 March 2018 during a storm event

(C) Culvert inlet below Kate Street, Indooroopilly QLD on 24 March 2018

Fig. 1-2 - Photographs of standard box culverts in eastern Australia

Current designs of standard culverts are similar to ancient designs, including the Roman culvert structures (O'CONNOR 1993, CHANSON 2002). Standard culverts are characterised by a significant afflux at the design discharge (HENDERSON 1966). The environmental impact of culverts on stream connectivity and fish passage may affect both upstream and downstream catchments with adverse effects on the ecology and fish movement (WARREN and PARDEW 1998, BRIGG and GALAROWICZ 2013). Common barriers to fish passage include perched outlet and excessive vertical drop at the culvert exit, high velocity and insufficient water depth in the culvert barrel, debris accumulation at the culvert inlet and standing waves in the outlet or inlet (OLSEN and TULLIS 2013). High water velocities in the culvert barrel can also create culvert exit velocities, which generate scour hole development and create perched outlet situations.

Several jurisdictions, local government and agencies have developed culvert design guidelines to ensure that new culvert designs allow for upstream fish passage. Most guidelines are typically based upon a number of simple criteria, including bulk velocity and minimum water depth (Table 1-1). Table 1-1 regroups recommendations, observations and design guidelines for freshwater fish passage in standard culverts. A general trend suggests that box culverts are most effective designs than pipe culverts in terms of fish passage (BRIGG and GALAROWICZ 2013). For a number of applications, baffles and boundary roughening may be installed along the barrel invert to slow down the water flow, although the additional flow resistance can reduce drastically the culvert discharge capacity for a given afflux, thus increasing substantially the total cost of the culvert for a design discharge and maximum acceptable afflux.

Considering fish negotiating a culvert structure, the upstream passage may be analysed like an optimisation process, in a manner comparable to that used in competitive swimming (WANG and WANG 2006). It could be implied that fish might change their swimming stroke to minimise drag and maximise their efficiency during upstream culvert passage, as observed with competitive swimmers during international meetings (KOLMOGOROV and DUPLISHCHEVA 1992, WEI et al. 2014). This brings up questions on the applicability of some literature data on fish swim tunnel tests for upstream fish passage in prototype culverts (KATOPODIS and GERVAIS 2016, WANG and CHANSON 2017, MOORE et al. 2018). Indeed field observations (BEHLKE et al. 1991, BLANK 2008, GOETTEL et al. 2015) and near-full-scale experiments (GARDNER 2006, WANG et al. 2016a, CABONCE et al. 2017) reported fish seeking low velocity zones, associated with high turbulence intensity levels, to pass through culverts structures. These hydrodynamic conditions are markedly different from tube testing conditions.

Several studies showed that small-bodied fish swim preferentially next to the culvert walls and in the corner regions (GARDNER 2006, JENSEN 2014, WANG et al. 2016a, CABONCE et al. 2017). Hydraulic engineering calculations may predict accurately the velocity field in these regions which are low-velocity zones with $0 < V_x < V_{mean}$, V_x being the local time-averaged longitudinal velocity and V_{mean} the bulk velocity ([1]) (WANG and CHANSON 2017, ZHANG and CHANSON 2018). In the present document, a new approach for hydraulic engineering design guidelines of fish-friendly box culverts is presented, with a focus on small-body fish with weak swimming capability. It is the aim of this study to contribute to the development of newer simple engineering guidelines of economically-viable fish friendly culverts.

[1] The bulk velocity is the cross-sectional averaged velocity: V = Q/A with Q the water discharge and A the flow cross-section area measured normal to the streamlines.

Table 1-1 - Observations, recommendations and design guidelines for freshwater fish passage in standard culverts

Reference	Country & Region	Targeted fish species	Design criteria	Flow conditions	Type of study
CHORDA et al. (1995)	France		Baffles	S_o = 0.01 to 0.05	Laboratory work
FAIRFULL and WHITERIDGE (2003)	Australia		Depth > 0.2-0.3 m V_{mean} < 0.3 m/s for d < 0. 5 m	Smooth culvert	Guidelines
BATES et al. (2003)	USA, Washington	Trout, pink salmon, chum salmon, chinook, coho, sockeye, steelhead	Depth > 0.24 to 0.30 m V_{mean} < 0.61 to 1.83 m/s	Smooth culvert	Guidelines
GARDNER (2006)	USA, North Carolina	Bluehead chub (*Nocomis leptocephalus*), redbreast Sunfish (*Lepomis auritus*), Johnny Darter (*Etheostoma nigrum*), bluegill (*Lepomis macrochirus*), margined madtom (*Noturus insignis*), swallowtail shiner (*Notropisprocne*)	V_{mean} < 0.55 m/s	Smooth culvert	Laboratory work. Box culvert geometry.
CAHOON et al. (2007)	USA, Montana	Yellowstone cutthroat trout (*Oncorhynchus clarkii bouvieri*), rainbow trout (*Oncorhynchus mykiss*)	V_{mean} < 1.9-2.7 m/s		Guidelines. Box culvert geometry.
BLANK (2008)	USA, Montana	Yellowstone cutthroat trout (*Oncorhynchus clarkii bouvieri*)	V_x(z = 0.06 m) < 1 to 2 m/s q < 0.4 to 0.57 m^2/s	Base flow: 0.28 m^3/s S_o = 0.02 to 0.05	Field observations. Box culvert geometry.
KILGORE et al. (2010), SCHALL et al. (2012)	USA		Minimum water depth for $Q > Q_{min}$ Maximum bulk velocity for $Q < Q_{high}$	$Q_{min} < Q_{high} < Q_{des}$	Guidelines
ESPLIN and HOTCHKISS (2011)	USA, Utah	Leatherside chub (*Lepidomeda aliciae*), speckled dace (*Rhinichthys osculus*)	$V_x(z = 0.05\text{ m}) < U_{fish}$	Smooth and substrate boundaries	Laboratory work. Box culvert geometry.

Reference	Country & Region	Targeted fish species	Design criteria	Flow conditions	Type of study
MONK and HOTCHKISS (2012)	USA, Utah	Leatherside chub (*Lepidomeda aliciae*), speckled dace (*Rhinichthys osculus*)	$V_x(z = 0.02\text{ m}) < U_{fish}$	$L_{barrel} \sim 20$ m $0.5 < Q < 1.6\ m^3/s$ $0.073 < q < 0.24\ m^2/s$	Field observations. Box culvert geometry.
COURRET (2014)	France	Trout, European bullhead (*Cottus gobio*), brook lamprey (*Lampetra planeri*), spined loach (*Cobitis taenia*), common minnow (*Phoxinus phoxinus*), eel, crayfish	Baffles, macro-roughness	From drought to 2-3 times the mean annual discharge	Guidelines
DWA (2014)	Germany	European species incl. barbel, brown trout, eel, grayling, salmon, ...	$V_{mean} < U_{fish}$ Depth > 2.5×Fish height Baffles/crossbars, macro-roughness	$Q_{330} < Q < Q_{30}$ each year	Guidelines

Notes: d: water depth; L_{barrel}: barrel length; Q: water discharge; Q_{30}: flow rate occurring no more than 30 days per year; Q_{330}: flow rate occurring no more than 330 days per year; q: unit discharge; S_o: bed slope; V_{mean}: bulk velocity; V_x: local longitudinal velocity; z: vertical elevation above the invert.

2. HYDRAULIC DESIGN OF STANDARD BOX CULVERTS - CURRENT PRACTICE

2.1 PRESENTATION

The primary constraints in the design of a culvert are: (a) the total cost must always be minimum, and (b) the afflux must be small and preferably minimum. The afflux is the rise in upstream water elevation caused by the presence of the culvert structure and it constitutes a quantitative measure of upstream flooding induced by the culvert. Based upon current design practices, the hydraulic characteristics of a culvert are the design discharge and the maximum acceptable afflux, between headwater and tailwater. The design discharge and corresponding water level in the natural stream in absence of culvert structure at design flow conditions are deduced from the hydrological and hydraulic engineering data of the site, in relation to the purpose of the culvert. Afflux must be minimised to reduce upstream flooding. The hydraulic design is basically an optimum compromise between discharge capacity, afflux and construction costs. While the key objective is to keep the cost of the culvert to a minimum, some consideration must be taken to avoid upstream afflux and flooding by keeping the head loss small and to avoid scour downstream of the culvert outlet if a hydraulic jump might take place, by placement of some scour protection. Most culverts are designed to operate as open channel systems at design flow conditions, with critical flow conditions occurring in the barrel at design discharge in order to maximise the discharge per unit width and to reduce the barrel cross-section.

For standard culverts, the traditional design procedure can be divided into two parts. First a system analysis must be carried out to ascertain the culvert purposes, design data, and constraints. This first stage leads to the selection of the design rainfall and runoff event, with an estimate of the design discharge Q_{des}. The maximum acceptable afflux h_{max} at design flow conditions is typically set by the asset owner based upon an impact assessment of the culvert structure on the upstream catchment and embankment. During the second stage, the barrel size is selected by an iterative procedure, in which both inlet control and outlet control calculations are conducted. Inlet control means that the hydraulic control is located at the entrance: e.g., critical flow conditions take place in the barrel with free-surface inlet. Outlet control implies that the culvert flow is controlled at the outlet, i.e. by the tailwater conditions. At the end, the optimum size is the smallest barrel size allowing for inlet control operation. If this cannot be achieved, the system analysis must be reconsidered.

2.2 DESIGN APPROACH

The barrel size is selected by a test-and-trial procedure. Both inlet control and outlet control calculations are performed for design flow conditions. At the end, the optimum size is the smallest barrel size allowing for inlet control operation (HERR and BOSSY 1965, CHANSON 1999,2004). The key input parameters are the design discharge Q_{des} and the maximum acceptable afflux h_{max}. The key output is the minimum internal barrel width B_{min} to achieve inlet control. The construction cost may be optimised using a multi-cell culvert of precast rectangular box elements, and the number of cells N_{cell} becomes a basic output.

Other relevant design parameters are the bed slope S_o and the tailwater depth d_{tw}. The bed slope is directly proportional to the natural drop in bed elevation along the culvert length, which would be equal to the maximum acceptable head loss for a zero afflux design. Indirectly the bed slope affects the tailwater depth. The tailwater depth is linked to the topography of the downstream catchment (shape, longitudinal slope, boundary roughness, possibly tailwater effects). In a number of cases, the tailwater depth is equal to or close to the uniform equilibrium flow depth in the downstream flood plain for the design discharge assuming a mild slope. More generally, basic hydraulic calculations are conducted assuming implicitly a mild slope, for which both gradually-varied flow and uniform equilibrium flow conditions correspond to a subcritical flow motion (Appendix B).

Finally a multicell culvert structure is designed with a number N_{cell} of identical cells and it is assumed that the water discharge in each cell is equal: $Q_{cell} = Q/N_{cell}$.

2.3 DESIGN PROCEDURE

The calculations of the culvert barrel size are iterative (Concrete Pipe Association of Australasia 1991,2012, CHANSON 2004). The iteration steps include:

(a) Selection of the barrel and element dimensions (e.g. barrel length, precast box internal dimensions).

(b) Assuming inlet control conditions, calculation of the upstream total head $H_{hw}^{(ic)}$ corresponding to the design discharge Q_{des}. The calculations may be based upon formulae or design charts, and the are repeated for different barrel sizes (e.g. number of cells) until the upstream total head $H_{hw}^{(ic)}$ fulfill the design specifications in terms of maximum acceptable afflux h_{max}.

(c) Assuming outlet control conditions, design charts are used to estimate the head loss ΔH from the culvert inlet to culvert outlet for the design discharge Q_{des}. The upstream total head $H_{hw}^{(oc)}$ is then $H_{hw}^{(oc)} = H_{tw} + \Delta H$, where H_{tw} is the downstream, tailwater total head.

(d) Inlet and outlet control results are compared: $H_{des} = H_{hw}^{(ic)} \gtrless H_{hw}^{(oc)}$? The larger value controls the culvert flow operation: e.g., if $H_{hw}^{(ic)} < H_{hw}^{(oc)}$, outlet control operation takes place. When the inlet control design head $H_{hw}^{(ic)}$ is larger than $H_{hw}^{(oc)}$, inlet control operation is confirmed and the barrel size is correct. In the negative, the barrel size must be increased and the iterations continue.

(e) Finally the free-board is checked for a minimum clearance of about 20% between the water surface and obvert. With inlet control, the water depth is about critical in the barrel and the relative free-board is $(D_{cell}-d_c)/D_{cell}$, where D_{cell} is the internal barrel height and d_c is the critical flow depth in the barrel at design flow. If the free-board is less than 20%, a wider barrel must be considered and the iterations continue.

2.4 APPLICATION

In absence of culvert, and at design flow conditions, the flow depth in the flood plain corresponds to a subcritical flow motion for most situations on a mild slope (App. B). Since the flood plain flow is subcritical, such flow conditions do correspond to the culvert's tailwater flow conditions for all cases. At design flow, the tailwater specific energy is:

$$E_{tw} = d_{tw} + \frac{V_{tw}^2}{2 \times g} = d_{tw} + \frac{Q_{des}^2}{2 \times g \times A_{tw}^2} \qquad (2\text{-}1)$$

where A is the river channel flow cross-section area for the water depth d and the subscript tw refers to the tailwater conditions.

With zero afflux, the upstream and downstream flow depths are identical and equal to d_{tw}, and the culvert barrel will operate with inlet control conditions. Outlet control calculations are not required practically.

With a maximum acceptable afflux h_{max}, the upstream flow depth is $d_{hw} = d_{tw} + h_{max}$ and the corresponding upstream specific energy is:

$$E_{hw} = d_{hw} + \frac{V_{hw}^2}{2 \times g} = d_{tw} + h_{max} + \frac{Q_{des}^2}{2 \times g \times A_{hw}^2} \qquad (2\text{-}2)$$

where the subscript hw refers to the headwater conditions.

First inlet control calculations are conducted. The input variables are the internal barrel height D_{cell}, the upstream specific energy E_{hw} and possibly the inlet wingwall configuration. The output is the discharge per unit width q_{des}. The minimum internal barrel width is then: $B_{min} = Q_{des}/q_{des}$. For a multicell culvert structure with N_{cell} identical cells of internal width B_{cell}, the number of cells is the smallest integer larger than B_{min}/B_{cell}. Conversely, for a structure made of N_{cell} identical barrel cells, the design chart gives the expected afflux ([2]).

Second outlet control calculations are performed. The input data are the barrel's internal cross-section area A_{barrel}, the barrel length L_{barrel}, an entrance loss coefficient (e.g. $k_e = 0.5$) and the water discharge Q_{des} ([3]). The calculation output is the head loss ΔH. The upstream total head with outlet

[2] The expected afflux is typically less than h_{max} since $N_{cell} \times B_{cell} > B_{min}$.

[3] For a multicell culvert structure, calculations may be conducted for a single cell. The input is then the cell's

control is then $H_{hw}^{(oc)} = H_{tw} + \Delta H$. In first approximation, the afflux is about: $\Delta H - L_{culv} \times S_o$, where L_{culv} is the total culvert length measured from inlet lip to outlet lip, and S_o is the longitudinal bed slope ($S_o = \sin\theta$).

Finally the free-board with inlet control operation is about $(D_{cell}-d_c)/D_{cell}$.

2.5 COMMENTS

Current hydraulic design of standard box culvert is an optimisation process for the design flow conditions. Consideration for non-design flow conditions is limited.

In practice, design engineers must ensure that a culvert operates safely for a broader range of flow conditions. Damage (scouring, piping, breaching) to the embankment and to the downstream river bed may occur in several cases:

- the apron is too short and/or too shallow to prevent bed scour,
- flow conditions larger than design flow conditions, leading to embankment overtopping,
- inlet blockage by debris,
- sediment siltation and build up in culvert barrel,
- unusual flood event during construction periods,
- poor construction of the barrel, inlet or outlet,
- poor shapes of the inlet and outlet, or misalignment of barrel in relation to the stream flow direction, resulting in poor discharge capacity,
- wrong dimensions of the barrel.

Practically, it is extremely important to consider the following points:

- the culvert is designed for the reference flow conditions (i.e. design flow conditions);
- for discharges larger than the design discharge, it may be acceptable to tolerate some erosion and damage; however, it is essential that the safety of the embankment is ensured;
- for discharges smaller than the design discharge, perfect performances are expected: that is, (a) the culvert must operate safely and (b) there must be no maintenance issue.

These objectives are achieved by (1) a correct design of culvert barrel dimensions, (2) a correct design of inlet and outlet to guide the flow into and out of the culvert barrel and (3) provision of a downstream apron to prevent downstream bed scour, if required.

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internal cross-section area $A_{cell} = D_{cell} \times B_{cell}$, the barrel length L_{barrel}, an entrance loss coefficient (e.g. $k_e = 0.5$) and the water discharge $Q_{des} = Q_{des}/N_{cell}$ per cell.

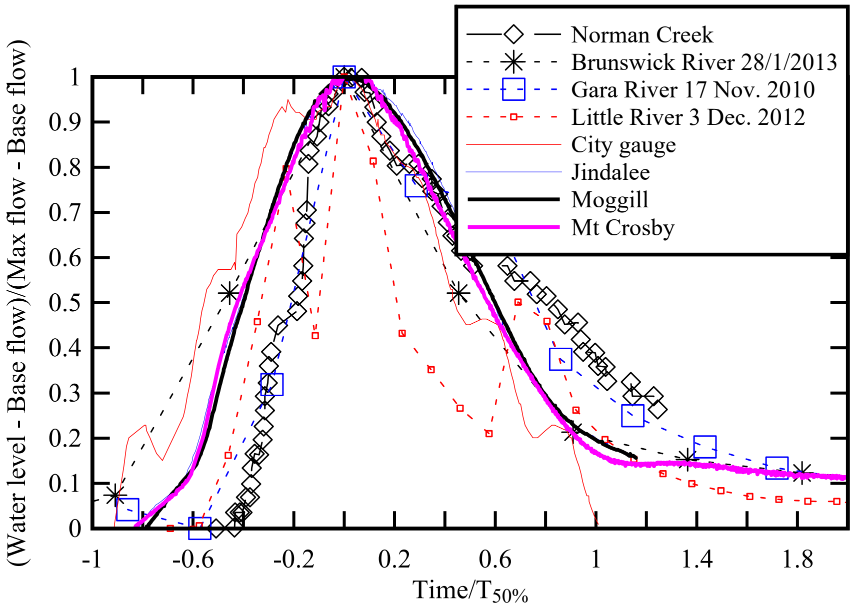
3. DEVELOPING HYDRAULIC ENGINEERING GUIDELINES FOR SMALL-BODY-FISH PASSAGE IN STANDARD BOX CULVERTS

3.1 PRESENTATION

In terms of hydraulic engineering design, the optimum size of a culvert is the smallest barrel size allowing for inlet control operation (section 2). The current engineering approach is focused on design flow conditions and does not consider upstream fish passage requirements.

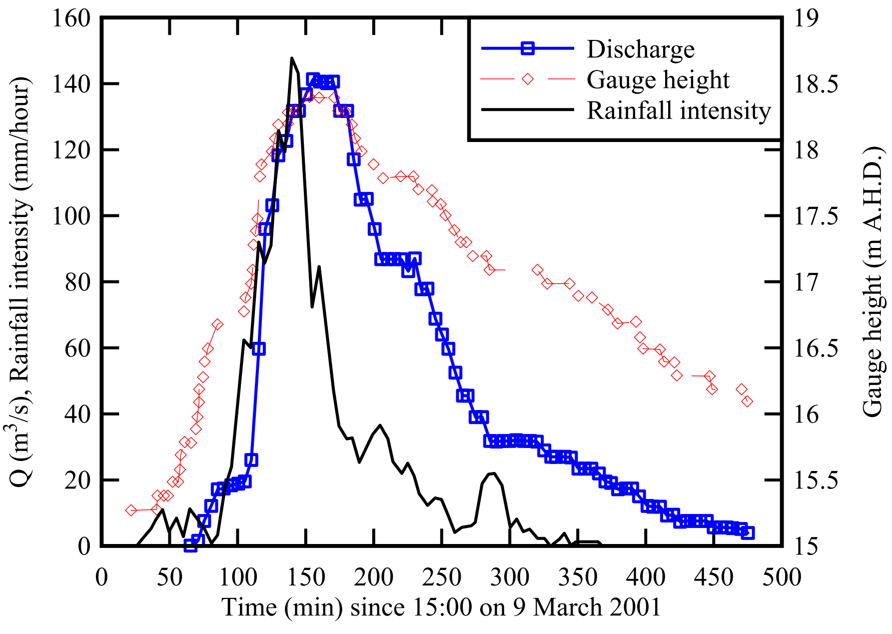
When fish passage is important during rainfall and runoff events (e.g. flood) (Fig. 3-1), fish passage in culvert should be optimised for a range of less-than-design flow conditions, in particular below a certain discharge threshold Q_1, set such as $Q_1 < Q_{des}$ with Q_{des} the design flow rate (CABONCE et al. 2018). Above that threshold, i.e. $Q_1 < Q < Q_{des}$, the culvert structure may be optimised in terms of discharge capacity for a given design afflux. A different reasoning could suggest that fish passage in culvert may be optimised for some duration of the design rainfall-and-runoff event, outside of the peak flow period, e.g. ±20% of event duration around the peak flow. In both approaches, the culvert design is optimised in terms of fish passage for flow conditions corresponding to less-than-design flow conditions, for which current engineering guidelines are very limited and hydraulic engineering calculations typically not provided. When a culvert discharges all the time, and fish passage requirements are not directly linked to some major hydrological event, another approach for determination of fish passage discharge range may be its proper operation for certain proportion of the year, e.g. 300 days. In Germany, fish-friendly culvert design guidelines recommend fish passage for discharges Q within $Q_{330} < Q < Q_{30}$, with Q_{30} the flow rate occurring less than 30 days per year and Q_{330} the flow rate occurring no more than 330 days per year (DWA 2014).

A massive challenge for the design of fish-friendly culverts is matching swimming performance data to hydrodynamic measurements. Many swim tests lack standardised test methods, i.e. two different studies rarely use the same protocol. and the output is either a single-point measurement or a bulk velocity (KATOPODIS and GERVAIS 2016). In contrast, physical and numerical modelling of fluid dynamics deliver very-detailed flow maps, including contours of time-averaged velocity based upon hundreds of measurement points, and turbulence properties. Matching hydrodynamic observations and swimming performance information can be very difficult, when data were collected with markedly different spatial and temporal resolution, standardisation level and metrology expertise.



(A) Dimensionless water level hydrographs during single flood events in eastern Australia (Data: NSW Office of Water, Bureau of Meteorology)

River	Location	Catchment area (km^2)	Flood event
Norman Creek	Holland Park QLD	8.5	9 March 2001
Brunswick River	Durrumbul NSW	34	28 Jan. 2003
Gara River	Willow Glen NSW	121	17 Nov. 2010
Little River	Obley 2 NSW	612	3 Dec. 2013
Brisbane River	Brisbane City QLD, Jindalee, Moggill, Mt Crosby	13,600	12-14 Jan. 2011



(B) Rainfall intensity and discharge stage hydrograph during a flood event on 9 March 2001 - Holland Park East station on Norman Creek catchment (catchment area: 8.5 km^2) (Data: YU et al. 2007)

Fig. 3-1 - Storm event hydrographs in eastern Australia

Recent studies showed that small-bodied fish tend to swim next to the culvert walls and in the corner regions (GARDNER 2006, JENSEN 2014, WANG et al. 2016a). This has been clearly documented with small-body Australian fish species (WANG et al. 2016a, CABONCE et al. 2017, GOODRICH et al. 2018). A study showed further the adverse effects of strong recirculation, i.e. negative velocities, on small-bodied fish (CABONCE et al. 2018), suggesting that many types of apertures might be detrimental, e.g. baffles.

Current hydraulic engineering design guidelines do not encompass less-than-design flow conditions ($Q < Q_{des}$), although fish swim as soon as there is water in culvert, i.e. $Q > 0$. New design guidelines for fish-friendly standard box culverts must be considered using a different (i.e. new) approach. While overseas experiences might be relevant, Australia is characterised by a markedly different hydrology and fish species. Australia is a relatively dry continent with long droughts as well as very-intense rainstorm and runoff events (TIMBALL 2010, NATHAN 2012, DOWDY et al. 2015). In this study, the targeted fish species are small-body Australian native species, including juvenile fish, with weak swimming ability ([1]), with flood flows being one of the main triggers for fish to initiate migrations.

3.2 NEW DESIGN GUIDELINE APPROACH

3.2.1 Presentation

New design guidelines for fish-friendly box culverts are proposed, based upon three key concepts:

(1) The culvert design is optimised for fish passage for $Q_{min} < Q < Q_1$; and it is optimised in terms of flood capacity for $Q_1 < Q < Q_{des}$.

(2) Since small-body fish swim next to the channel corners and sidewalls, the swimming performance data are related to a portion (i.e. percentage) of the wetted flow area where:

$$0 < V_x < U_{fish} \tag{3-1}$$

with V_x the local time-averaged longitudinal velocity component and U_{fish} a characteristic fish speed ([2]).

(3) Guidelines are developed for most common structures: $L_{barrel} < 12\text{-}15$ m and multicell culverts with internal cell width $0.5 < B_{cell} < 2.5$ m, because these structures constitute the large majority of road crossing barriers in New South Wales (GORDOS, M. 2016, *Pers. Comm.*); for other

[1] including Empire Gudgeon, Firetail Gudgeon, Western Carp Gudgeon Striped Gudeon, Mountain Galaxias Southern Pygmy Perch, Unspecked Hardyhead, Common Jollytail, Olive Perchlet, Fly-specked Hardyhead, Australian Smelt, Duboulay's Rainbowfish, as well as juvenile Australian Bass, Macquarie Perch, Murray Cod, River Blackfish, Golden Perch, Eel-tailed Catfish, Silver Perch and Spangled Perch.

[2] For example, set by a regulatory agency or based upon biological observations and swimming test data.

structures, a basic methodology and calculation flow chart may be provided.

3.2.2 Discussion

The design optimisation is considered in relation to a discharge threshold Q_1, rather than flood event duration. The selection is consistent with current engineering practices since the discharge is a design parameter, and most rainfall and runoff events in eastern Australia tend to have a self-similar shape as illustrated in Figure 3-1A. Figure 3-1A presents dimensionless water level hydrograph data for single flood events in a variety of catchments located in eastern Australia. These include coastal as well as inland locations, with very diverse rainfall patterns and catchment sizes ([3]). Details of the catchments are listed in the figure caption.

Note that the selection of a very-low design discharge could result in a smaller cheaper culvert structure, with potentially poor ecological outcomes in terms of biological considerations. The timing of fish passage must be considered as part of the determination of appropriate hydrology and hydraulic engineering design specifications for culvert structures (HOTCHKISS and FREY 2007). Fish presence may vary between watersheds, and fish migration timing might show great disparity with respect to stream flows and species. Fish movement in a catchment may be triggered by time of year, runoff events and a number of environmental factors. In Australia, for example, flows are one of the main triggers for fish to initiate migrations, with high flows being a significant trigger response (GORDOS, M. 2018, *Person. Comm.*).

A very-novel feature is to deliver a minimum relative flow area where the longitudinal water velocity is less than the characteristic fish speed (Eq. (3-1)). This region is called a low-velocity zone and would be typically along the wetted perimeter and next to the channel corners. The argumentation is based upon two fundamental results:

(a) the rate of work and energy required by fish to thrust itself against the flow is proportional to the cube of the local fluid velocity V_x (WANG and CHANSON 2018), and

(b) small-body Australian fish swim next to rectangular channel corners and sidewalls (WANG et al. 2016a, CABONCE et al. 2017, GOODRICH et al. 2018).

Two practical questions derive from the approach: what are the influence of the relative threshold Q_1/Q_{des} and of the percentage of flow area on the size and cost of box culvert structures?

3.3 INFLUENCE ON CULVERT STRUCTURE SIZE AND COSTS

A sensitivity analysis was conducted for two multicell box culvert structures, typical of two-lane

[3] All the catchments are located in the South-Eastern Australia (SEA) climatic region (TIMBAL 2010).

roadway projects (Table 3-1). Natural tailwater conditions were used: i.e., gauge data (Culvert 1) and uniform equilibrium flow conditions (Culvert 2). The culvert barrel size was calculated to achieve the smallest barrel size with inlet control for the design flow rate Q_{des} and maximum acceptable afflux h_{max}, with the culvert barrel invert at natural ground level (Section 2). The calculation output was the number of cells $(N_{cell})_{des}$, listed in Table 3-1.

For less-than-design flow conditions, hydraulic engineering calculations were based upon one-dimensional calculations, using complete calculations and numerical modelling (Appendix C). In addition and for Culvert 1, computational fluid dynamics (CFD) calculations were undertaken. The focus of these calculations was to test a lower invert, allowing to retain a 0.3 m deep pool of water in the culvert barrel during dry to very-low flow conditions.

The hydraulic engineering calculations were performed for a range of less-than-design discharges $0.1 < Q/Q_{des} < 0.5$. The tailwater conditions were subcritical and the culvert flow remained subcritical with outlet control. Characteristic fish speeds were considered from $0.2 < U_{fish} < 1$ m/s based upon the targeted fish specie (GORDOS, M. 2018, *Person. Com.*). Percentages of flow area corresponding to low-velocity zones were tested between 10% and 20%.

Basic results are reported in Figure 3-2 and the full details are reported in Appendix D. Figure 3-2 presents the increase in number of culvert barrel cells to achieve the low-velocity zone target, i.e. 15% of flow area where $0 < V_x < U_{fish}$. For each graph, the vertical axis is the characteristic fish speed U_{fish} and the lower horizontal axis is the dimensionless number of cells $N_{cell}/(N_{cell})_{des}$, where N_{cell} is the number of barrel cells for the fish-friendly culvert design and $(N_{cell})_{des}$ is the number of barrel cells for optimum flood capacity design. The upper horizontal axis is the relative increase in number of barrel cells compared to the optimum flood capacity design. As a first approximation, the result would correspond to the increase in culvert construction costs to achieve fish passage, in the form of additional precast cell units, although, depending upon the site, the final design might require construction of a second structure in an anabranch or selection of a bridge structure instead of a culvert, all at a greater cost.

Table 3-1 - Characteristics of multicell box culvert structures

	Culvert 1	Culvert 1b	Culvert 2
Hydrology	Gara River NSW	Gara River NSW	
Tailwater conditions	Gauge data	Gauge data	Uniform equilibrium flow
S_o	0	0	0.012
Design event	1-in-1 year event ([1])	1-in-1 year event ([1])	
Q_{des} (m^3/s)	20.0	--	4.8
Q_{des} (ML/day)	1,728	--	415

q_{des} (m^2/s)	1.92	1.92	0.78
L_{barrel} (m)	8	8	14
D_{cell} (m)	1.0	1.3	0.5
B_{cell} (m)	1.3	1.0	1.0
Boundary roughness	smooth concrete	smooth concrete	smooth concrete
Barrel invert	natural ground level	0.3 m below natural ground level	natural ground level
Maximum acceptable afflux h_{max} (m)	0.55	0.55	0.20
Number of cells $(N_{cell})_{des}$	8 ([2])	1	7 ([2])
$(V_{mean})_{des}$ (m/s)	2.7	1.9	2.0

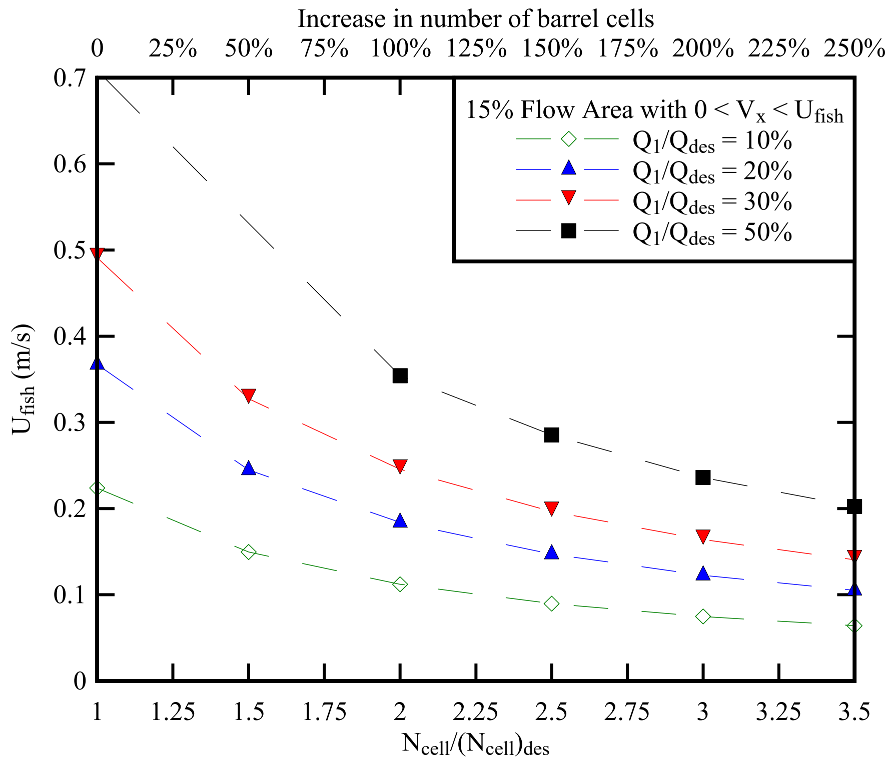
Notes: ([1]) based upon river gauge data record from 15 March 2008 to 15 March 2018; ([2]) Minimum cross-section area for inlet control operation at design flow conditions.

Overall the results demonstrated conclusively that the cost of a fish-friendly box culvert increases with decreasing characteristic fish speed U_{fish}, increasing discharge threshold Q_1/Q_{des} and increasing percentage of flow area:

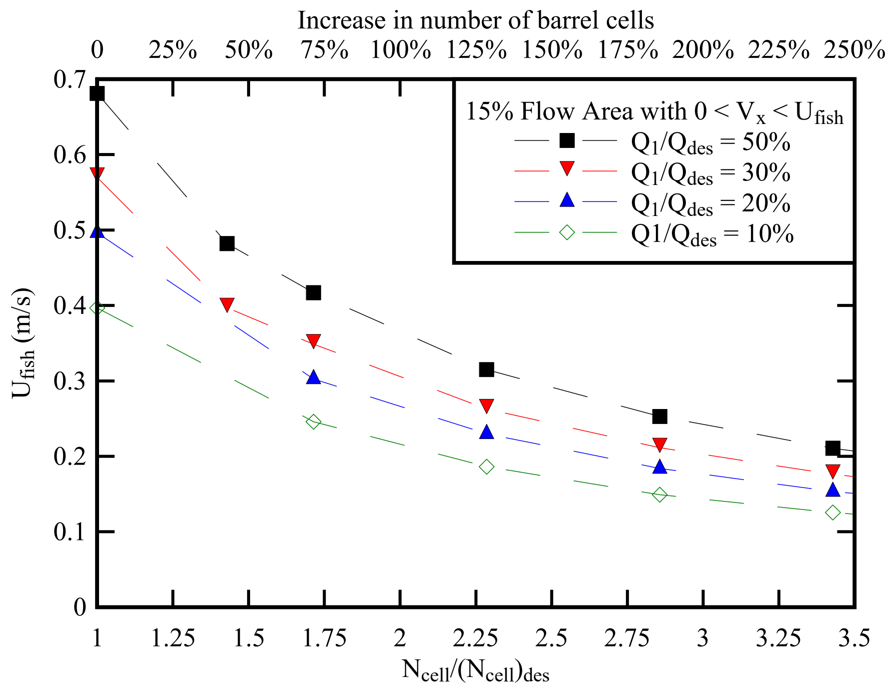
$$\text{Culvert Cost} \uparrow \equiv \begin{cases} U_{fish} \downarrow \\ Q_1 / Q_{des} \uparrow \\ \%\text{flow area} \uparrow \end{cases} \tag{3-2}$$

The calculations showed a critical impact of the characteristic speed U_{fish} of targeted fish specie. Very expensive structures would be required to pass small-body fish with characteristic swimming speeds less than 0.3 m/s, within the range of investigated flow and boundary conditions. Conversely, a targeted fish speed U_{fish} > 0.7 m/s seems achievable for Q < 0.5×Q_{des}. An important design parameter is the discharge threshold Q_1/Q_{des}. The provision of fish passage capability for Q > 0.5×Q_{des} would be prohibitive to small-body fish. The selection of 10% < Q_1/Q_{des} < 30% tends to be achievable with more moderate increase in culvert size (Fig.3-2).

The relative size of the low-velocity zone impacts also on the structure costs (App. D). Based upon detailed physical modelling for flow boundary conditions with which fish endurance was tested (WANG et al. 2016b, CABONCE et al. 2017), 15% of flow area with 0 < V_x < U_{fish} may be an appropriate target.



(A) Culvert 1



(B) Culvert 2

Fig. 3-2 - Relative increase in number of cells for fish-friendly multicell box culverts as a function of the threshold discharge Q_1/Q_{des} and characteristic fish speed U_{fish}, with 15% of flow area where $0 < V_x < U_{fish}$

3.4 DISCUSSION

Detailed CFD calculations were conducted for a culvert barrel invert installed 0.3 m below the natural ground level (Fig. 3-3, App. D) ([4]). First, the results showed a significantly more complicated flow field, compared to a culvert barrel invert at natural ground level. This is illustrated in Figure 3-4, presenting longitudinal velocity contours at several barrel cross-sections. For that flow condition, 22% of the pooled culvert flow area experienced a longitudinal velocity V_x such as $0 < V_x < 0.3$ m/s. Second, the calculations demonstrated the same trends as for a culvert barrel invert at natural ground level. Namely, the cost of fish-friendly box culvert increases with decreasing characteristic fish speed U_{fish}, increasing discharge threshold Q_1/Q_{des} and increasing percentage of flow area. Full results are presented in Appendix D.

In summary, the design of a culvert with recessed "wet" cell(s) ([5]) may provide an alternative for low-velocity zones with minimum water depth. It would however require more advanced fluid dynamic calculations and be more expensive to build than culvert structures with barrel invert lying on natural ground level.

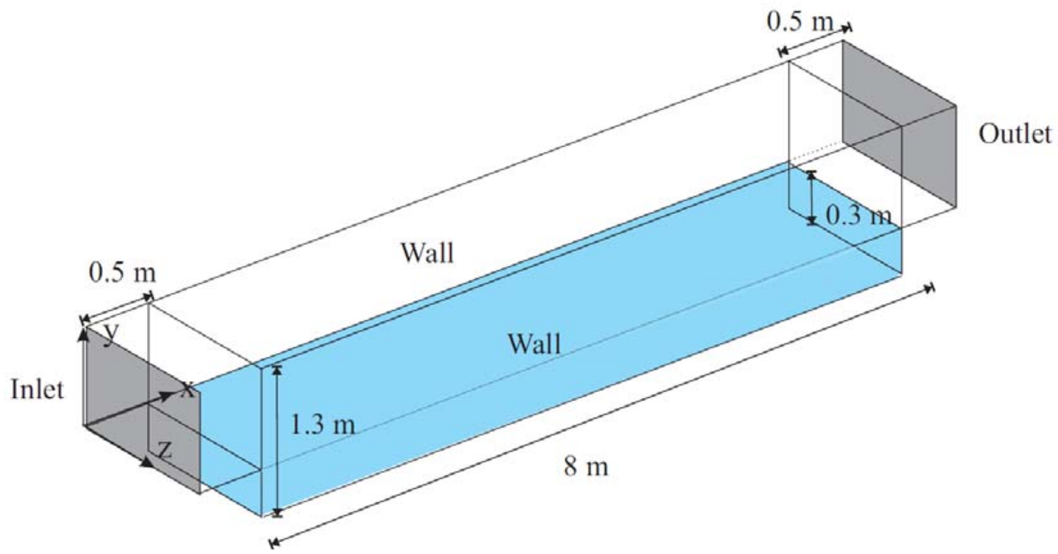


Fig. 3-3 - Definition sketch of pooled (recessed) culvert barrel (Culvert 1b)

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[4] The recessed culvert barrel invert configuration was based upon current Australian guideline recommendations (FAIRFULL and WHITRIDGE 2003).

[5] also called low flow channel.

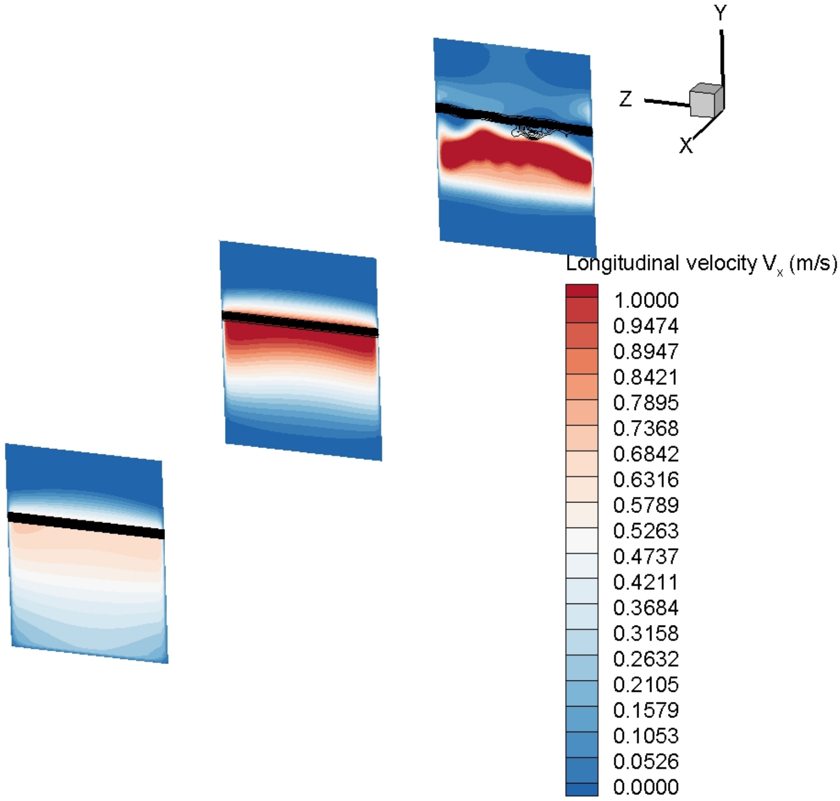

Fig. 3-4 - Longitudinal velocity contours in the culvert barrel (Culvert 1b) for q/q_{des} = 20% - Black line indicate the free-surface - Flow direction from top right to bottom left, Barrel water depth: 0.83 m, V_{mean} = 0.45 m/s

4. CONCLUDING REMARKS

New design guidelines for fish-friendly multicell box culverts are proposed, based upon two basic and simple concepts: (a) the culvert design is optimised for fish passage for $Q_{min} < Q < Q_1$, and for flood capacity for $Q_1 < Q < Q_{des}$, and (b) low-velocity zones are defined in terms of a percentage of the wetted flow area where $0 < V_x < U_{fish}$, with V_x the local longitudinal velocity component and U_{fish} a characteristic fish speed linked to swimming performances of targeted fish specie. The development aims to deliver simple guidelines ([1]), in line with current engineering practices. Low-velocity zones (LVZs) are provided along the wetted perimeter and next to the culvert barrel corners, where small-body-mass fish swim and can minimise their energy expenditure. Importantly, this new approach is based upon an accurate knowledge of the entire flow field in the barrel, specifically the longitudinal velocity map rather the bulk velocity, because small-body fish swim next to boundaries.

The influence of the relative threshold Q_1/Q_{des}, critical fish speed U_{fish} and percentage of flow area on the size of box culvert structures was assessed based upon hydraulic engineering calculations. Calculations were conducted for smooth culvert barrel invert at natural ground level. Figure 4-1 presents some basic finding for $Q_1/Q_{des} = 0.2$, critical fish speeds $0.1 < U_{fish} < 0.6$ m/s and 15% of flow area on the size where $0 < V_x < U_{fish}$ for two smooth box multicell culvert systems. Overall the results suggested that the increase in culvert size and cost might become very significant for $U_{fish} <$ 0.3 m/s and $Q_1/Q_{des} > 0.3$, when providing 15% flow area with $0 < V_x < U_{fish}$, with smooth culvert barrel. The increase in culvert size would correspond to an increase in culvert construction costs to achieve fish passage compared to a traditional engineering design approach.

When the characteristic swimming speed of the targeted fish specie is less than 0.3 m/s ($U_{fish} <$ 0. 3 m/s), a different design approach might be required. One option could target a lower relative threshold Q_1/Q_{des}. Another option could involve a design incorporating a barrel cell with very-low-velocity zones. This could be achieved with boundary roughening and addition of apertures (e.g. baffles), although negative velocities and strong recirculation must be avoided for small-bodied fish, since a recent study demonstrated their adverse effects (CABONCE et al. 2017,2018).

Further detailed CFD calculations for recessed cell(s) with lower invert indicated similar trends as those for a culvert barrel invert at natural ground level in terms of cost increase. The results however showed a significantly more complicated hydrodynamic field in the barrel, compared to a culvert barrel invert at natural ground level, in addition to increased construction costs.

Finally it is acknowledged that the design approach is focused in culvert barrel design. Complete

[1] that is, for multicell box culvert structures with identical (or nearly-identical) smooth barrel cells.

design guidelines must further include inlet and outlet design recommendations.

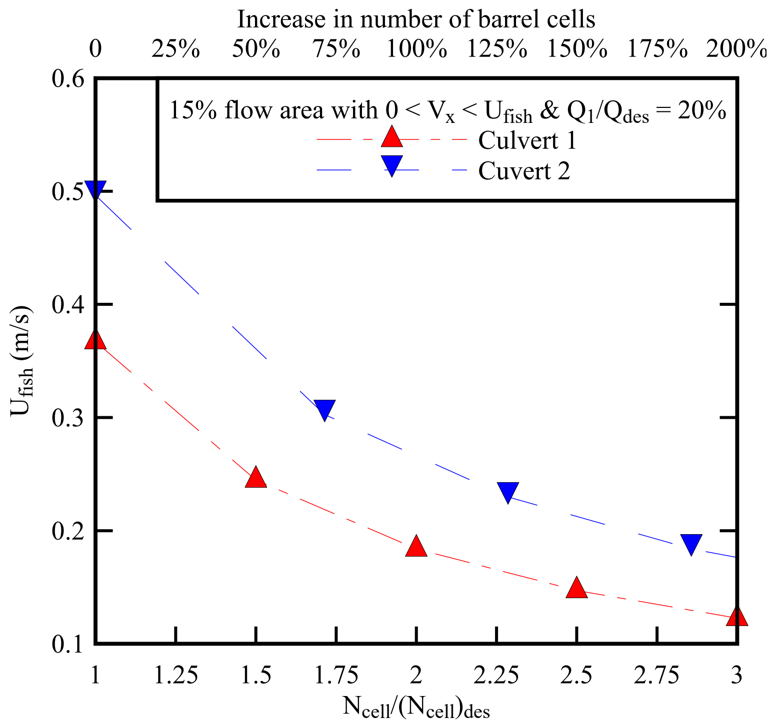

Fig. 4-1 - Relative increase in number of cells for fish-friendly multicell box culverts as a function of the characteristic fish speed U_{fish}, for $Q_1/Q_{des} = 0.2$ and with 15% of flow area where $0 < V_x < U_{fish}$ - Culvert characteristics listed in Table 3-1

5. ACKNOWLEDGEMENTS

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APPENDIX A - GLOSSARY OF TECHNICAL TERMS

Abutment: part of the valley side against which the dam or bridge is constructed.

Accretion: increase of channel bed elevation resulting from the accumulation of sediment deposits.

Advection: movement of a mass of fluid which causes change in temperature or in other physical or chemical properties of fluid.

AEP: probability of exceedance of a given discharge within a period of one year, generally expressed in percentage.

Aerobic: activity involving, needing, oxygen. Aerobic fish swimming can be maintained for an extended period without fatigue and metabolic activity utilises only red muscle tissues.

Afflux: rise of water level above normal level (i.e. natural flood level) on the upstream side of a culvert or of an obstruction in a channel. In the United States, it is commonly referred to as maximum backwater.

Aggradation: rise in channel bed elevation caused by deposition of sediment material. Another term is accretion.

Alternate depth: In open channel flow, for a given flow rate and channel geometry, the relationship between the specific energy and flow depth indicates that, for a given specific energy, there is no real solution (i.e. no possible flow), one solution (i.e. critical flow) or two solutions for the flow depth. In the latter case, the two flow depths are called alternate depths: one corresponds to a subcritical flow and the second to a supercritical flow.

Anaerobic: activity not requiring oxygen. Anaerobic fish swimming cannot be maintained for an extended period and metabolic activity utilises only white muscle tissue.

Analytical model: system of mathematical equations which are the algebraic solutions of the fundamental equations.

APELT: Colin J. APELT is an Emeritus Professor in civil engineering at the University of Queensland (Australia).

Apron: the area at the downstream end of a weir or culvert outlet to protect against erosion and scouring by water.

ARI: Average value of period between exceedances of a given discharge, expressed typically as 1 in Y years.

Armouring: progressive coarsening of the bed material resulting from the erosion of fine particles. The remaining coarse material layer forms an armour, protecting further bed erosion.

Backwater: In a subcritical flow, the longitudinal flow profile is controlled by the downstream flow conditions: e.g., an obstacle, a structure, a change of cross-section. Any downstream control structure (e.g. bridge piers, weir) induces a backwater effect. More generally the term backwater calculations or backwater profile refer to the calculation of the longitudinal free-surface profile in open channel. The term is used for both supercritical and subcritical free-surface flows.

Backwater calculation: calculation of the free-surface profile in open channels. The first successful calculations were developed by the Frenchman J.B. BÉLANGER who used a finite difference step method for integrating the equations (BELANGER 1828).

BARRÉ de SAINT-VENANT: Adhémar Jean Claude BARRÉ de SAINT-VENANT (1797-1886), French engineer of the Corps des Ponts-et-Chaussées, developed the equation of motion of a fluid particle in terms of the shear and normal forces exerted on it (BARRÉ de SAINT-VENANT 1871a,b).

Barrel: for a culvert, central section where the cross-section is minimum. Another term is the throat.

Bed load: sediment material transported by rolling, sliding and saltation motion along the bed.

BÉLANGER: Jean-Baptiste Ch. BÉLANGER (1789-1874) was a French hydraulician and professor at the Ecole Nationale Supérieure des Ponts et Chaussées (Paris). He suggested first the application of the momentum principle to hydraulic jump flow (BELANGER 1841).

Bélanger equation: momentum equation applied across a hydraulic jump in a horizontal rectangular channel and named after J.B.C. BÉLANGER (CHANSON 2009).

BERNOULLI: Daniel BERNOULLI (1700-1782) was a Swiss mathematician, physicist and botanist who developed the Bernoulli equation in his "*Hydrodynamica, de viribus et motibus fluidorum*" textbook (1st draft in 1733, 1st publication in 1738, Strasbourg).

Bernoulli equation: basic principle derived from the Navier-Stokes equation, assuming no energy loss.

BORDA: Jean-Charles de BORDA (1733-1799) was a French mathematician and military engineer, who investigated the flow through orifices and developed the Borda mouthpiece.

Bottom outlet: opening near the bottom of a dam for draining the reservoir and flushing out reservoir sediments.

Boundary layer: flow region next to a solid boundary where the flow field is affected by the presence of the boundary and where friction plays an essential part. A boundary layer flow is characterised by a range of velocities across the boundary layer region from zero at the boundary to the free-stream velocity at the outer edge of the boundary layer.

BOUSSINESQ: Joseph Valentin BOUSSINESQ (1842-1929) was a French hydrodynamicist and Professor at the Sorbonne University (Paris). His treatise "Essai sur la théorie des eaux courantes" (BOUSSINESQ 1877) is an outstanding contribution in the hydraulics literature.

Boussinesq coefficient: momentum correction coefficient named after J.V. BOUSSINESQ who first proposed it (BOUSSINESQ 1877).

Boussinesq-Favre wave: an undular surge (see Undular surge).

BOYS: P.F.D. du BOYS (1847-1924) was a French hydraulic engineer. He made a major contribution to the understanding of sediment transport and bed-load transport (BOYS 1879).

BRESSE: Jacques Antoine Charles BRESSE (1822-1883) was a French applied mathematician and hydraulician. He was Professor at the Ecole Nationale Supérieure des Ponts et Chaussées, Paris as successor of J.B.C. BELANGER. His contribution to gradually-varied flows in open channel hydraulics is considerable (BRESSE 1860).

Broad-crested weir: A weir with a flat long crest is called a broad-crested weir when the ratio of crest length to upstream head is greater than 1.5 to 3. When the crest is long enough, the pressure distribution along the crest is hydrostatic and the flow depth equals the critical flow depth $d_c = (q^2/g)^{1/3}$.

BUAT: Comte Pierre Louis George du BUAT (1734-1809) was a French military engineer and hydraulician, and friend of Abbé C. BOSSUT. Du BUAT is considered as the pioneer of experimental hydraulics. His textbook (BUAT 1779) was a major contribution to flow resistance in pipes, open channel hydraulics and sediment transport.

Bulk velocity: cross-sectional averaged velocity or mean flow velocity.

Byewash: channel to carry spilled or wasted waters, i.e. ancient name for a spillway.

Cartesian co-ordinate: one of three co-ordinates that locate a point in space and measure its distance from one of three intersecting co-ordinate planes measured parallel to that one of three straight-line axes that is the intersection of the other two planes. It is named after the French mathematician René DESCARTES.

CHÉZY: Antoine CHÉZY (1717-1798) (or Antoine de CHÉZY) was a French engineer and member of the French Corps des Ponts-et-Chaussées. He designed canals for the water supply of the city of Paris. In 1768, he proposed a resistance formula for open channel flows called the Chézy equation.

Chézy coefficient: resistance coefficient for open channel flows first introduced by the Frenchman A. CHÉZY. Although some thought to be a constant, the coefficient is a function of the relative roughness and Reynolds number.

Choke: In open channel flow, a channel contraction might obstruct the flow and induce the appearance of critical flow conditions (i.e. control section). Such a constriction is sometimes called a 'choke'.

Choking flow: critical flow in a channel contraction. The term is used for both open channel flow and compressible flow.

Cofferdam: temporary structure enclosing all or part of the construction area so that construction can proceed in dry conditions. A diversion cofferdam diverts a stream into a pipe or channel.

Cohesive sediment: sediment material of very small sizes (i.e. less than 50 μm) for which cohesive bonds between particles (e.g. intermolecular forces) are significant and affect the material properties.

Conjugate depth: in open channel flow, another name for sequent depth.

Control: Considering an open channel, subcritical flows are controlled by the downstream conditions. This is called a downstream flow control. Conversely supercritical flows are controlled only by the upstream flow conditions, i.e. upstream flow control.

Control section: in an open channel, cross-section where critical flow conditions take place. The concept of control, hydraulic control and control section are used with the same meaning.

Control surface: is the boundary of a control volume.

Control volume: refers to a region in space and is used in the analysis of situations where flow occurs into and out of the space.

CORIOLIS: Gustave Gaspard CORIOLIS (1792-1843) was a French mathematician and engineer of the 'Corps des Ponts-et-Chaussées' who first described the Coriolis force (i.e. effect of motion on a rotating body).

Coriolis coefficient: kinetic energy correction coefficient named after G.G. CORIOLIS who introduced first this velocity correction coefficient (CORIOLIS 1836).

Critical depth: is the flow depth for which the mean specific energy is minimum.

Critical flow conditions: In open channel flows, the flow conditions such as the specific energy (of the mean flow) is minimum are called the critical flow conditions. If the flow is critical, small changes in specific energy cause large changes in flow depth (BAKHMETEFF 1912, CHANSON 2006,2008). In practice, critical flow over a long reach of channel is unstable.

Critical slope: When the uniform equilibrium flow depth is equal to the critical flow depth, the uniform equilibrium flow is critical, and the slope is called a critical slope. Critical slopes are seldom found in nature, because critical flow motion is unstable.

Culvert: covered channel of relatively short length installed to pass water through an embankment, e.g. highway, railroad, dam.

DARCY: Henri Philibert Gaspard DARCY (1805-1858) was a French civil engineer. He studied at Ecole Polytechnique between 1821 and 1823, and later at the Ecole Nationale Supérieure des Ponts et Chaussées (BROWN 2002). He performed numerous experiments of flow resistance in pipes (DARCY 1858) and in open channels (DARCY and BAZIN 1865), and of seepage flow in porous media (DARCY 1856). He gave his name to the Darcy-Weisbach friction factor and to the Darcy law in porous media.

Darcy-Weisbach friction factor: dimensionless parameter characterising the friction loss in a flow. It is named after the Frenchman H.P.G. DARCY and the German J. WEISBACH.

Debris: Debris comprise mainly large boulders, rock fragments, gravel-sized to clay-sized material, tree and wood material that accumulate in creeks.

Degradation: lowering in channel bed elevation resulting from the erosion of sediments.

Dimensional analysis: organisation technique used to reduce the complexity of a study, by expressing the relevant parameters in terms of numerical magnitude and associated units, and grouping them into dimensionless numbers. The use of dimensionless numbers increases the generality of the results.

Diversion channel: waterway used to divert water from its natural course.

Drainage layer: layer of pervious material to relieve pore pressures and/or to facilitate drainage: e.g., drainage layer in an earthfill dam.

Drop structure: single step structure characterised by a sudden decrease in bed elevation.

DUPUIT: Arsène Jules Etienne Juvénal DUPUIT (1804-1866) was a French engineer and economist.

Earth dam: massive earthen embankment with sloping faces and made watertight.

Eddy viscosity: another name for the momentum exchange coefficient. It is also called "eddy coefficient" by SCHLICHTING (1979). (See Momentum exchange coefficient)

Embankment: fill material (e.g. earth, rock) placed with sloping sides and with a length greater than its height.

Explicit method: calculation containing only independent variables; numerical method in which the flow properties at one point are computed as functions of known flow conditions only.

Face: external surface which limits a structure: e.g. water face (i.e. upstream face) of a weir.

Fawer jump: undular hydraulic jump.

Finite differences: approximate solutions of partial differential equations which consists essentially in replacing each partial derivative by a ratio of differences between two immediate values: e.g., $\partial V/\partial t \approx \delta V/\delta t$. The method was first introduced by RUNGE (1908).

Fixed-bed channel: The bed and sidewalls are non-erodible boundaries. Neither erosion nor accretion occurs.

Flash flood: flood of short duration with a relatively high peak flow rate.

Flood frequency: frequency with which a flood has the probability of recurring. Measures of the rarity of a rainfall event include the Average Recurrence Interval (ARI) and Annual Exceedance Probability (AEP). When ARI is expressed in years, the relationship between AEP and ARI is:

$$\mathrm{AEP} = 1 - e^{-1/\mathrm{ARI}}$$

Generally it is preferable to express the rarity of an event in terms of AEP (ARR 1987).

Free-surface: interface between a liquid and a gas. More generally a free-surface is the interface between the fluid (at rest or in motion) and the atmosphere. In two-phase gas-liquid flow, the free-surface region includes also the air-water interface of gas bubbles and liquid drops.

Free-surface aeration: Natural aeration occurring at the free surface of high velocity flows is referred to as free surface aeration or self-aeration.

Freeboard: free-space clearance between the mean free-surface level and the roof (i.e. obvert). In a culvert, the free-board in the barrel must be at least 20% to prevent adverse effect (CHANSON 2004, p. 445).

FROUDE: William FROUDE (1810-1879) was a English naval architect and hydrodynamicist who invented the dynamometer and used it for the testing of model ships in towing tanks. He was assisted by his son Robert Edmund FROUDE who, after the death of his father, continued some of his work. In 1868, he used REECH's law of similarity to study the resistance of model ships.

Froude number: The Froude number is proportional to the square root of the ratio of the inertial forces over the weight of fluid. The Froude number is used generally for scaling free surface flows, open channels and hydraulic structures. Although the dimensionless number was named after William FROUDE, several French researchers used it before (DUPUIT 1848, BRESSE 1860, BAZIN 1865). Ferdinand REECH introduced the dimensionless number for testing ships and propellers in 1852. The number is also called the Reech-Froude number.

G.K. formula: empirical resistance formula developed by the Swiss engineers E. GANGUILLET and W.R. KUTTER in 1869.

Gate: valve or system for controlling the passage of a fluid. In open channels the two most common types of gates are the underflow gate and the overflow gate.

GAUCKLER: Philippe Gaspard GAUCKLER (1826-1905) was a French engineer and member of the French Corps des Ponts-et-Chaussées. He re-analysed the experimental data for open channel flows of DARCY and BAZIN (1865), and presented in 1867 a flow resistance formula, i.e. Gauckler-Manning formula, too often called improperly the Manning equation (GAUCKLER 1867).

Gradually varied flow: is characterised by relatively small changes in velocity and pressure distributions over a short distance (e.g. long waterway).

Headwater depth: upstream flow depth.

Headwater level: upstream free-surface elevation.

Hydraulic diameter: is defined as the equivalent pipe diameter: i.e., four times the cross-section area divided by the wetted perimeter. The concept was first expressed by the Frenchman P.L.G. du BUAT (BUAT 1779).

Hydraulic jump: transition from a rapid supercritical flow to a slow flow motion (i.e. subcritical flow). Although the hydraulic jump was described by LEONARDO DA VINCI, the first experimental investigations were published by Giorgio BIDONE in 1820. The present theory of the jump was developed by BELANGER (1841) and verified experimentally since (e.g. BAKHMETEFF and MATZKE 1936).

Ideal fluid: frictionless and incompressible fluid. An ideal fluid has zero viscosity: i.e., it cannot sustain shear stress at any point.

Implicit method: calculation in which the dependent variable and the one or more independent variables are not separated on opposite sides of the equation; numerical method in which the flow properties at one point are computed as functions of both independent and dependent flow conditions.

Inflow: (1) upstream flow; (2) incoming flow.

Inlet: (1) upstream opening of a culvert, pipe or channel; (2) a tidal inlet is a narrow water passage between peninsulas or islands.

Inlet control: In a culvert, inlet control flow conditions mean that the hydraulic control is located at the entrance: e.g., critical flow conditions take place in the barrel with free-surface inlet.

Intake: any structure in a reservoir through which water can be drawn into a waterway or pipe. By extension, upstream end of a channel.

International system of units: see Système international d'unités.

Invert: (1) lowest portion of the internal cross-section of a conduit; (2) channel bed of a spillway; (3) bottom of a culvert barrel.

Inviscid flow: is a non-viscous flow.

IPPEN: Arthur Thomas IPPEN (1907-1974) was Professor in hydrodynamics and hydraulic engineering at M.I.T. (USA). Born in London of German parents, educated in Germany (Technische Hochschule in Aachen), he moved to USA in 1932, where he obtained the M.S. and Ph.D. degrees at the California Institute of Technology. There he worked on high-speed free-surface flows with Theodore von KARMAN. In 1945 he was appointed at M.I.T. until his retirement in 1973.

Irrotational flow: is defined as a zero vorticity flow. Fluid particles within a region have no rotation. If a frictionless fluid has no rotation at rest, any later motion of the fluid will be irrotational. In irrotational flow each element of the moving fluid undergoes no net rotation, with respect to chosen coordinate axes, from one instant to another.

J.H.R.C.: Jump Height Rating Curve.

J.H.R.L.: Jump Height Rating Level.

KARMAN: Theodore von KARMAN (or von KÁRMÁN) (1881-1963) was a Hungarian fluid dynamicist and aerodynamicist who worked in Germany (1906 to 1929) and later in USA. He was a student of Ludwig PRANDTL in Germany. He gave his name to the vortex shedding behind a cylinder, i.e. Karman vortex street.

Karman constant (or von Karman constant): pseudo-universal constant K of proportionality between the Prandtl mixing length and the distance from the boundary. Experimental results indicate that $K = 0.4$.

KENNEDY: Professor John Fisher KENNEDY (1933-1991) was a hydraulic professor at the University of Iowa, USA. He succeeded Hunter ROUSE as head of the Iowa Institute of Hydraulic Research.

KEULEGAN: Garbis Hovannes KEULEGAN (1890-1989) was an Armenian mathematician who worked as hydraulician for the US Bureau of Standards since its creation in 1932.

Left abutment: abutment on the left-hand side of an observer when looking downstream.

Left bank (left wall): Looking downstream, the left bank or the left channel wall is on the left.

Lining: coating on a channel bed to provide water tightness, to prevent erosion or to reduce friction.

Low-velocity zone (LVZ): flow area where the time-averaged longitudinal velocity V_x is small, typically substantially smaller than the bulk velocity V_{mean}. Low-velocity zones are essential for successful upstream passage because the rate of work and energy required by fish to thrust themselves against the current is proportional to the cube of the local fluid velocity (WANG and CHANSON 2018). Recent work on small-body fish showed further that LVZs should not exhibit strong recirculation or negative velocity (CABONCE et al. 2018).

L.V.Z.: see Low Velocity Zone.

McKAY: Professor Gordon M. McKAY (1913-1989) was Professor in Civil Engineering at the University of Queensland.

MANNING: Robert MANNING (1816-1897) was Chief Engineer of the Office of Public Works, Ireland. In 1889, he presented two formulae (MANNING 1890). One became the so-called Gauckler-Manning formula, but Robert MANNING preferred the second formula. It must be noted that the Gauckler-Manning formula was proposed first by the Frenchman P.G. GAUCKLER (GAUCKLER 1867).

Meandering channel: alluvial stream characterised by a series of alternating bends (i.e. meanders) as a result of alluvial processes.

M.E.L. culvert: see Minimum Energy Loss culvert.

Metabolism: chemical processes occurring within living organisms in order to maintain life. For example, those causing food to be used for energy and growth.

Metric system: see Système métrique.

Mild slope: A channel slope is usually classified by comparing the uniform equilibrium flow depth to the critical flow depth. When the uniform equilibrium flow depth is larger than the critical flow depth, the uniform equilibrium flow is subcritical, and the slope is called a mild slope.

Minimum energy loss culvert: culvert designed with very smooth shapes to minimise energy losses. The design of a minimum energy loss culvert is associated with the concept of constant total head. The inlet and outlet must be streamlined in such a way that significant form losses are avoided (APELT 1983).

Momentum exchange coefficient: In turbulent flows the apparent kinematic viscosity, or kinematic eddy viscosity, is analogous to the kinematic viscosity in laminar flows. It is called the momentum exchange coefficient, the eddy viscosity or the eddy coefficient. The momentum exchange coefficient is proportional to the ratio of shear stress to strain rate, and first introduced by the Frenchman J.V. BOUSSINESQ (1877,1896).

NAVIER: Louis Marie Henri NAVIER (1785-1835) was a French engineer who primarily designed bridges but also extended EULER's equations of motion (NAVIER 1823).

Navier-Stokes equation: momentum equation applied to a small control volume of incompressible fluid. It is usually written in vector notation. The equation was first derived by L. NAVIER in 1822 and S.D. POISSON in 1829 by a different method. It was derived later in a more modern manner by A.J.C. BARRÉ de SAINT-VENANT in 1843 and G.G. STOKES in 1845.

Nomograph: abaque for graphical calculations; design chart.

Non uniform equilibrium flow: the velocity vector varies from place to place at any instant: steady non uniform flow (e.g. flow through an expanding tube at a constant rate) and unsteady non uniform flow (e.g. flow through an expanding tube at an increasing flow rate).

Normal depth: uniform equilibrium open channel flow depth.

Obvert: roof of the barrel of a culvert. Another name is soffit.

One-dimensional flow: neglects the variations and changes in velocity and pressure transverse to the main flow direction. An example of one-dimensional flow can be the flow through a pipe.

One-dimensional model: model defined with one spatial coordinate, the variables being averaged in the other two directions.

Outflow: downstream flow.

Outlet: (1) downstream opening of a pipe, culvert or canal; (2) artificial or natural escape channel.

Outlet control: In a culvert, outlet control flow conditions imply that the culvert flow is controlled at the outlet, i.e. by the tailwater conditions.

PASCAL: Blaise PASCAL (1623-1662) was a French mathematician, physicist and philosopher. He developed the modern theory of probability. Between 1646 and 1648, he formulated the concept of pressure and showed that the pressure in a fluid is transmitted through the fluid in all directions.

Pascal: unit of pressure named after the Frenchman B. PASCAL: one Pascal equals a Newton per square-metre.

PITOT: Henri PITOT (1695-1771) was a French mathematician, astronomer and hydraulician. He was a member of the French Académie des Sciences from 1724. He invented the Pitot tube to measure flow velocity in the Seine river (first presentation in 1732 at the Académie des Sciences de Paris).

Pitot tube: device to measure flow velocity. The original Pitot tube consisted of two tubes, one with an opening facing the flow. L. PRANDTL developed an improved design (HOWE 1949) which provides the total head, piezometric head and velocity measurements: it is called a Prandtl-Pitot tube.

Potential flow: ideal-fluid flow with irrotational motion.

PRANDTL: Ludwig PRANDTL (1875-1953) was a German physicist and aerodynamicist who introduced the concept of boundary layer (PRANDTL 1904) and developed the turbulent 'mixing length' theory. He was Professor at the University of Göttingen.

PREISSMANN: Alexandre PREISSMANN (1916-1990) was born and educated in Switzerland. From 1958, he worked on the development of hydraulic mathematical models at SOGREAH in Grenoble (France).

Prismatic: A prismatic channel has an unique cross-sectional shape independent of the longitudinal distance along the flow direction. For example, a rectangular channel of constant width is prismatic.

Rapidly varied flow: is characterised by large changes over a short distance, e.g. sluice gate, hydraulic jump.

REECH: Ferdinand REECH (1805-1880) was a French naval instructor who proposed first the Reech-Froude number in 1852 for the testing of model ships and propellers.

REHBOCK: Theodor REHBOCK (1864-1950) was a German hydraulician and professor at the Technical University of Karlsruhe. His contribution to the design of hydraulic structures and physical modelling is important.

REYNOLDS: Osborne REYNOLDS (1842-1912) was a British physicist and mathematician who expressed first the Reynolds number (REYNOLDS 1883) and later the Reynolds stress (i.e. turbulent shear stress).

Reynolds number: dimensionless number proportional to the ratio of the inertial force over the viscous force.

Right abutment: abutment on the right-hand side of an observer when looking downstream.

Right bank (right wall): Looking downstream, the right bank or the right channel wall is on the right.

Roller: in hydraulics, large-scale turbulent eddy: e.g., the roller of a hydraulic jump.

S.A.F.: St Anthony's Falls hydraulic laboratory at the University of Minnesota (USA).

SAINT-VENANT: See BARRÉ de SAINT VENANT.

Scale effect: discrepancy between model and prototype resulting when one or more dimensionless parameters have different values in the model and prototype.

Scour: bed material removal caused by the eroding power of the flow.

Sediment: any material carried in suspension by the flow or as bed load which would settle to the bottom in absence of fluid motion.

Sediment load: material transported by a fluid in motion.

Sediment transport: transport of material by a fluid in motion.

Separation: In a boundary layer, a deceleration of fluid particles leading to a reversed flow within the boundary layer is called a separation. The decelerated fluid particles are forced outwards and the boundary layer is separated from the wall. At the point of separation, the velocity gradient normal to the wall is zero:

$$\left(\frac{\partial V_x}{\partial z}\right)_{z=0} = 0$$

Separation point: in a boundary layer, intersection of the solid boundary with the streamline dividing the separation zone and the deflected outer flow. The separation point is a stagnation point.

Sequent depth: In open channel flow, the solution of the momentum equation at a transition between supercritical and subcritical flow gives two flow depths (upstream and downstream flow depths). They are called sequent depths.

Similitude: correspondence between the behaviour of a model and that of its prototype, with or without geometric similarity. The correspondence is usually limited by scale effects.

Siphon: pipe system discharging waters between two reservoirs or above a dam in which the water pressure becomes sub-atmospheric. The shape of a simple siphon is close to an omega (i.e. Ω-shape). Inverted-siphons carry waters between two reservoirs with pressure larger than atmospheric. Their design follows approximately an U-shape. Inverted-siphons were commonly used by the Romans along their aqueducts to cross valleys.

Slope: (1) side of a hill; (2) inclined face of a canal (e.g. trapezoidal channel); (3) inclination of the channel bottom from the horizontal.

Sluice gate: underflow gate with a vertical sharp edge for stopping or regulating flow.

Soffit: roof of the barrel of a culvert. Another name is obvert.

Specific energy: quantity proportional to the energy per unit mass, measured with the channel bottom as the elevation datum, and expressed in metres of water. The specific is lined to the total head as; $E = H - z_o$, where z_o is the bed elevation. The concept of specific energy, first developed by B.A. BAKHMETEFF (1912), is commonly used in open channel flows.

Spillway: opening built into a dam or the side of a reservoir to release (to spill) excess flood waters.

Splitter: obstacle (e.g. concrete block, fin) installed on a chute to split the flow and to increase the energy dissipation.

Stage-discharge curve: relationship between discharge and free-surface elevation at a given location along a stream.

Stagnation point: is defined as the point where the velocity is zero. When a streamline intersects itself, the intersection is a stagnation point. For irrotational flow a streamline intersects itself at right-angle at a stagnation point.

Steady flow: occurs when conditions at any point of the fluid do not change with the time:

$$\frac{\partial V}{\partial t} = 0 \ \& \ \frac{\partial P}{\partial t} = 0$$

Steep slope: When the uniform equilibrium flow depth is smaller than the critical flow depth, the uniform equilibrium flow is supercritical, and the slope is called a steep slope. The notion of steep and mild slope is not only a function of the bed slope but is also a function of the flow resistance and implicitly of the flow rate and channel roughness.

Stilling basin: structure for dissipating the energy of the flow downstream of a spillway, outlet work, chute or canal structure. In many cases, a hydraulic jump is used as the energy dissipator within the stilling basin.

Storm water: excess water running off the surface of a drainage area during and immediately following a period of rain. In urban areas, waters drained off a catchment area during or after a heavy rainfall are usually conveyed in man-made storm waterways.

Storm waterway: channel built for carrying storm waters.

Streamline: is the line drawn so that the velocity vector is always tangential to it (i.e. no flow across a streamline). When the streamlines converge the velocity increases. The concept of streamline was first introduced by the Frenchman J.C. de BORDA.

Stream tube: is a filament of fluid bounded by streamlines.

Subcritical flow: In open channel the flow is defined as subcritical if the flow depth is larger than the critical flow depth. In practice, subcritical flows are controlled by the downstream flow conditions.

Supercritical flow: In open channel, when the flow depth is less than the critical flow depth, the flow is supercritical and the Froude number is larger than one. Supercritical flows are controlled from upstream.

Suspended load: transported sediment material maintained into suspension.

Swimming speed: Types of fish swimming speed performance are generally based on the duration of swimming to when a fish becomes fatigued and requires rest: endurance speed, also called sustained speed, prolonged speed, and burst or darting speed.

Système international d'unités: international system of units adopted in 1960 based on the metre-kilogram-second (MKS) system. It is commonly called SI unit system. The basic seven units are: for length, the metre; for mass, the kilogram; for time, the second; for electric current, the ampere; for luminous intensity, the candela; for amount of substance, the mole; for thermodynamic temperature, the Kelvin.

Système métrique: international decimal system of weights and measures which was adopted in 1795 during the French Révolution. Between 1791 and 1795, the Académie des Sciences de Paris prepared a logical system of units based on the metre for length and the kilogram for mass. The standard metre was defined as 1×10^{-7} times a meridional quadrant of earth. The gram was equal to the mass of 1 cm^3 of pure water at the temperature of its maximum density (i.e. 4 Celsius) and 1 kilogram equalled 1,000 grams. The litre was defined as the volume occupied by a cube of 1×10^3 cm^3.

T.W.R.C.: Tail Water Rating Curve.

T.W.R.L.: Tail Water Rating Level.

Tainter gate: is a radial gate.

Tailwater depth: downstream flow depth.

Tailwater level: downstream free-surface elevation.

Total head: The total head is proportional to the total energy per unit mass and per gravity unit. It is expressed in metres of water.

Training wall: sidewall of chute spillway.

Trashrack: screen comprising metal or reinforced concrete bars located at the intake of a waterway to prevent the progress of floating or submerged debris.

Turbulence: Flow motion characterised by its unpredictable behaviour, strong mixing properties and a broad spectrum of length scales (LESIEUR 1994).

Turbulent flow: In turbulent flows the fluid particles move in very irregular paths, causing an exchange of momentum from one portion of the fluid to another. Turbulent flows have great mixing potential and involve a wide range of eddy length scales.

Two-dimensional flow: all particles are assumed to flow in parallel planes along identical paths in each of these planes. There are no changes in flow normal to these planes. An example of two-dimensional flow can be an open channel flow in a wide rectangular channel.

U.S.A.C.E.: United States Army Corps of Engineers.

U.S.B.R.: United States Bureau of Reclamation.

Undular hydraulic jump: hydraulic jump characterised by steady stationary free-surface undulations downstream of the jump and by the absence of a formed roller. The undulations can extend far downstream of the jump with decaying wave lengths, and the undular jump occupies a significant length of the channel. It is usually observed for $1 < Fr_1 < 1.5$ to 3 (CHANSON and MONTES 1995). The first significant study of undular jump flow can be attributed to FAWER (1937) and undular jump flows should be called Fawer jump in homage to FAWER's work.

Uniform equilibrium flow: occurs when the velocity and depth are identically the same at every point, in magnitude and direction, for a given instant:

$$\frac{\partial V_{mean}}{\partial x} = 0 \quad \& \quad \frac{\partial d}{\partial x} = 0$$

in which time is held constant and ∂x is a longitudinal displacement. That is, steady uniform flow (e.g. liquid flow through a long pipe at a constant rate) and unsteady uniform flow (e.g. liquid flow through a long pipe at a decreasing rate).

Unsteady flow: The flow properties change with the time.

Uplift: upward pressure in the pores of a material (interstitial pressure) or on the base of a structure. Uplift pressures led to the destruction of stilling basins and even to the failures of concrete dams, e.g. Malpasset dam break in 1959.

Upstream flow conditions: flow conditions measured immediately upstream of the investigated control volume. Another name is headwater conditions.

Validation: comparison between model results and prototype data, to validate the model. The validation process must be conducted with prototype data that are different from that used to calibrate and to verify the model.

Vena contracta: minimum cross-section area of the flow (e.g. jet or nappe) discharging through an orifice, sluice gate or weir.

Viscosity: fluid property which characterises the fluid resistance to shear: i.e. resistance to a change in shape or movement of the surroundings.

Von Karman constant: see Karman constant.

Wake region: The separation region downstream of the streamline that separates from a boundary is called a wake or wake region.

Warrie: Australian Aboriginal name for 'rushing water'.

Waste waterway: old name for a spillway, particularly used in irrigation with reference to the waste of waters resulting from a spill.

Wasteweir: a spillway. The name refers to the waste of hydroelectric power or irrigation water resulting from the spill. A staircase wasteweir is a stepped spillway.

Water: common name applied to the liquid state of the hydrogen-oxygen combination H_2O. Although the molecular structure of water is simple, the physical and chemical properties of H_2O are unusually complicated. Water is a colourless, tasteless, and odourless liquid at room temperature. One most important property of water is its ability to dissolve many other substances: H_2O is frequently called the universal solvent. Under standard atmospheric pressure, the freezing point of water is 0 Celsius (273.16 K) and its boiling point is 100 Celsius (373.16 K).

Weak jump: A weak hydraulic jump is characterised by a marked roller, no free-surface undulation and low energy loss. It is usually observed after the disappearance of undular hydraulic jump with increasing upstream Froude numbers.

Weber number: Dimensionless number characterising the ratio of inertial forces over surface tension forces. It is relevant in problems with gas-liquid or liquid-liquid interfaces.

Weir: low river dam used to raise the upstream water level. Measuring weirs are built across a stream for the purpose of measuring the flow.

Wetted perimeter: Considering a cross-section (elected normal to the flowstreamlines, the wetted perimeter is the length of wetted contact between the flowing stream and the solid boundaries. For example, in a circular pipe flowing full, the wetted perimeter equals the circle perimeter.

Wetted surface: In open channel, the wetted surface refers to the surface area in contact with the flowing liquid.

Wing wall: sidewall of an inlet or outlet.

APPENDIX B - NATURAL FLOODPLAIN FLOW CALCULATIONS

B.1 PRESENTATION

The construction of a culvert structure impacts in a catchment. In absence of culvert, the river channel responds to floods in a deterministic way, set by basic principles. Namely the conservation of mass, momentum and energy. In many cases, the water depth d is equal to or close to the uniform equilibrium flow depth in the flood plain for the relevant discharge Q. In other situations, basic hydraulic calculations may be conducted assuming implicitly a mild slope, for which gradually-varied flow properties correspond to a subcritical flow motion and may be controlled by downstream boundary conditions., e.g. weir, riffles, change in bed slope.

In the following paragraph, both uniform equilibrium and gradually-varied flow calculations are presented. The results may be used to predict the tailwater conditions of a culvert structure installed in a mild slope river channel, when river gauge data are not available.

B.2 UNIFORM EQUILIBRIUM FLOW CONDITIONS (NORMAL FLOW CONDITIONS)

For a steady and uniform equilibrium open channel flow, the flow properties, i.e. depth d and mean velocity V_{mean}, are independent of time and of longitudinal position. The application of the momentum equation in an integral form yields an exact balance between the gravity force component in the flow direction and the boundary shear force. The result is a theoretical solution of the uniform equilibrium mean flow velocity:

$$V_{mean} = \sqrt{\frac{8 \times g}{f}} \times \sqrt{\frac{D_H}{4} \times \sin\theta} \qquad \text{uniform equilibrium flow} \quad \text{(B-1)}$$

where V_{mean} is the mean velocity, or cross-sectional averaged velocity, g is the gravity acceleration, f is the Darcy-Weisbach friction factor, D_H is the hydraulic diameter and θ is the angle between the channel bed and the horizontal. The hydraulic diameter is defined as: $D_H = 4 \times A/P_w$, with A the flow cross-section area ([1]) and P_w the wetted perimeter (Fig. B-1). The term sinθ is called the bed slope and denoted $S_o = \sin\theta$.

Equation (B-1) is solved iteratively since the friction factor is a function of the mean flow velocity and water depth (HENDERSON 1966, CHANSON 2004), while the water discharge Q must fulfil the conservation of mass:

$$Q = V_{mean} \times A \qquad \text{(B-2)}$$

[1] The flow cross-section area is measured perpendicular to the streamlines.

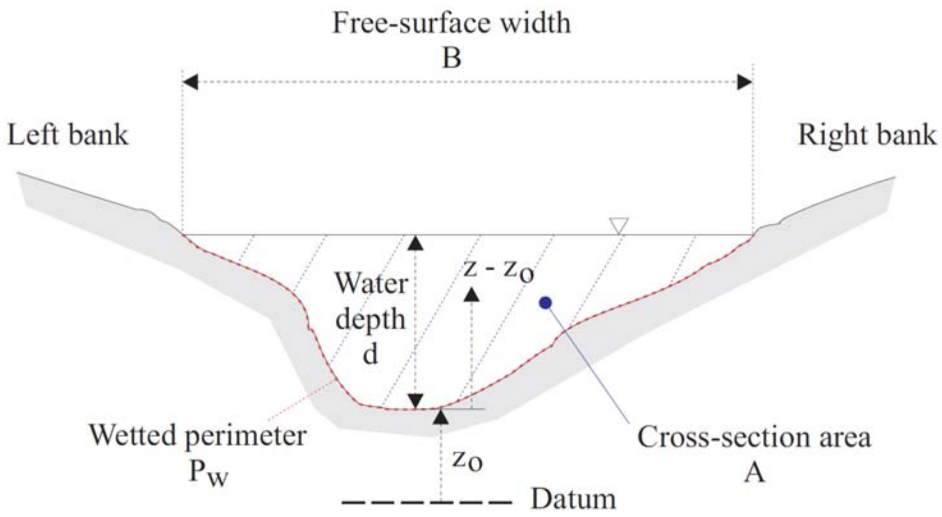

Fig. B-1 - Definition sketch of the flow area in a natural channel (looking downstream)

<u>Discussion</u>

In man-made channels, Equation (B-1) is the only correct expression of the momentum equation for uniform equilibrium flow in an open channel. In many practical turbulent flow situations, the Darcy-Weisbach friction factor may be estimated as:

$$\frac{1}{\sqrt{f}} = -2.0 \times \log_{10}\left(0.2695 \times \frac{k_s}{D_H} + \frac{2.51}{Re \times \sqrt{f}}\right) \tag{B-3}$$

where k_s is the equivalent sand roughness height of the boundary surface and Re is the Reynolds number $Re = \rho \times V_{mean} \times D_H/\mu$, with ρ the water density and μ the water dynamic viscosity ([2]). The Darcy-Weisbach friction factor appears on both sides of the Colebrook-White formula (Eq. (B-3)) which must be solved iteratively. It may also be solved graphically, e.g. using the Moody diagram. Typical values of equivalent sand roughness height and Darcy-Weisbach friction factor are reported in Table B-1.

In natural channels, the solution of the momentum equation may be rewritten in terms of empirical friction coefficient, such as a Chézy coefficient $C_{Chézy}$ (in $m^{1/2}.s$) or Gauckler-Manning coefficient n_{GM} (in $s/m^{1/3}$):

$$V_{mean} = C_{Chézy} \times \sqrt{\frac{D_H}{4} \times \sin\theta} \tag{B-4}$$

$$V_{mean} = \frac{1}{n_{GM}} \times \left(\frac{D_H}{4}\right)^{2/3} \times \sqrt{\sin\theta} \tag{B-5}$$

[2] At 20 Celsius, the water density and dynamic viscosity are respectively: $\rho = 998.2$ kg/m^3 and $\mu = 0.001005$ Pa.s.

Table B-1 - Typical equivalent sand roughness height and friction coefficients for concrete channels

Boundary surface	k_s (mm)	f	$C_{Chézy}$ ($m^{1/2}.s$)	n_{GM} ($s/m^{1/3}$)
Smooth concrete	0.3 to 3	0.012 to 0.02	62 to 80	0.012
Rough concrete	3 to 10	0.015 to 0.03	51 to 72	0.014

B.3 GRADUALLY-VARIED FLOW CONDITIONS

For a steady gradually-varied open channel flow, the differential form of the energy equation gives a relationship between the total head H and flow resistance in the form:

$$\frac{\partial H}{\partial x} = -S_f \qquad \text{gradually-varied flow} \quad \text{(B-6)}$$

where x is the longitudinal distance following the river channel and positive downstream, and S_f is the friction slope defined as:

$$S_f = \frac{f}{D_H} \times \frac{V_{mean}^2}{2 \times g} \qquad \text{(B-7)}$$

The friction slope is the slope of the total head line. For an open channel flow and hydrostatic pressure distributions, the total head is:

$$H = d \times \cos\theta + z_o + \frac{V_{mean}^2}{2 \times g} \qquad \text{(B-8)}$$

with z_o the invert elevation.

Also called the backwater equation, Equation (B-6) may be applied to gradually-varied steady flows in natural and man-made channels. It is valid within well-defined assumptions (HENDERSON 1966, CHANSON 2004).

The backwater equation may be integrated numerically, starting from a location of known water depth. A well-known integration method is the standard step method, distance calculated from depth, or depth calculated from distance (MONTES 1998).

Discussion

In natural channels, the friction slope might be expressed in terms of the empirical friction coefficient $C_{Chézy}$ and n_{GM}:

$$S_f = \frac{1}{C_{Chézy}^2} \times \frac{V_{mean}^2}{\frac{D_H}{4}} \qquad \text{(B-9)}$$

$$S_f = n_{GM}^2 \times \frac{V_{mean}^2}{\left(\frac{D_H}{4}\right)^{4/3}} \tag{B-10}$$

APPENDIX C - HYDRAULIC CALCULATIONS OF LESS-THAN-DESIGN FLOW IN A BOX CULVERT

C.1 PRESENTATION

A culvert is a covered channel designed to pass water beneath an embankment. The design can vary from a simple geometry (standard box culvert) to a hydraulically-smooth shape (M.E.L. culvert) (APELT 1983, CHANSON 1999). A culvert consists of three components: the intake or inlet, the barrel or throat, and the diffuser or outlet. Current engineering practices lead to an optimum design with the smallest barrel cross-section area with inlet control conditions for the design discharge and maximum acceptable afflux (CHANSON 2004, Concrete Pipe Association of Australia 2012). The following paragraphs discuss hydraulic calculations for less-than-design flow conditions of a culvert located in a mild slope flood plain.

For a flat flood plain and discharges substantially smaller than the design flow, the flow is subcritical in the entire culvert structure, accelerating in the inlet, faster in the barrel, and decelerating with some energy dissipation in the outlet. In the flood plain, the flow is subcritical in absence of culvert structure. With the culvert structure installed in the ground level, the tailwater conditions are the same as in absence of the culvert and the tailwater depth is denoted d_{tw} (Fig. C-1).

C.2 APPLICATION

For small discharges, the flow is subcritical and best controlled from downstream (Fig. C-1). Hydraulic calculations are performed from the tailwater where the water discharge Q and the flow depth d_{tw} are known ([1]). For a low flow, outlet control takes place basically (BATES et al. 2003, HOTCHKISS and FREI 2007). In the outlet, flow separation and form losses occur for expansion angles greater than 5º to 8º (MONTES 1998, CHANSON 2004). In practice, a majority of culvert outlets are built with wingwalls oriented between 30º to 60º from the culvert barrel centreline. The energy losses in the outlet are significant and must be estimated accurately. For a horizontal channel, the application of the energy equation between the culvert barrel exit and the tailwater flow yields:

$$d_{exit} + \frac{V_{exit}^2}{2 \times g} = d_{tw} + \frac{V_{tw}^2}{2 \times g} + K_{out} \times \left(\frac{V_{exit}^2}{2 \times g} - \frac{V_{tw}^2}{2 \times g} \right) \qquad \text{(C-1)}$$

[1] The relationship between water discharge and tailwater depth may be given by a water gauge data, or estimated based upon gradually-varied flow or uniform equilibrium flow calculations (Appendix B).

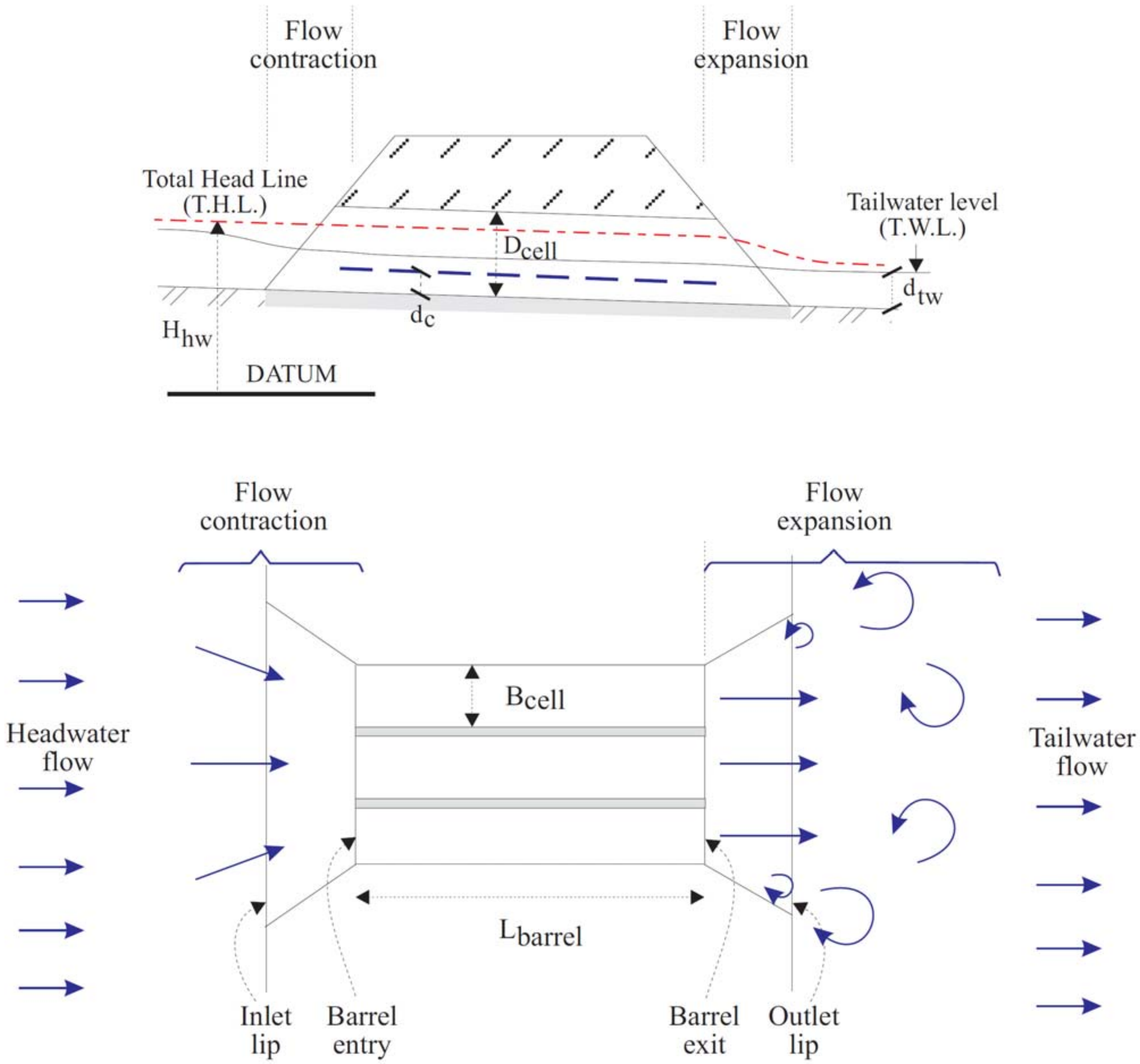

Fig. C-1 - Definition sketch of standard box culvert operation for less-than-design flow conditions in a mild slope flood plain

where d is the water depth, V is the mean velocity, the subscript exit refers to the culvert barrel exit flow conditions, the subscript tw refers to the tailwater flow conditions, and the coefficient K_{out} is an outlet loss coefficient ([2]). Experimental observations indicated that $0.8 < K_{out} < 1.1$ for a divergence angle from centreline greater than 20º (MONTES 1998) (Fig. C-2). It is commonly assumed $K_{out} = 1$ (HENDERSON 1966). Combining Equation (C-1) and the equation of conservation of mass, it yields the flow properties at the downstream end of the culvert barrel: i.e., the depth d_{exit} and velocity V_{exit}.

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[2] For $K_{out} = 1$, Equation (C-1) yields the Borda-Carnot formula for a sudden expansion.

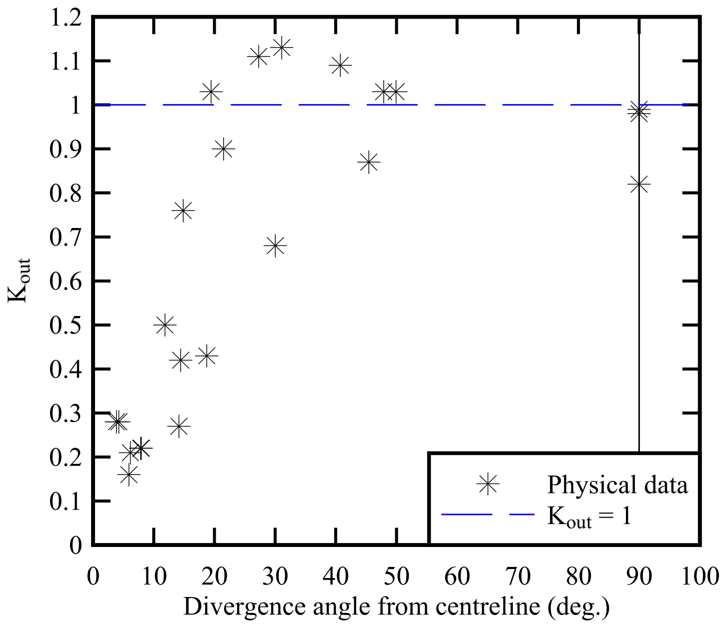


Fig. C-2 - Straight expansion loss coefficient in open channels as a function of the opening angle relative to the channel centreline

Upstream of the barrel exit, the flow from the upstream flood plain into the inlet and culvert barrel may be considered gradually-varied. In the culvert barrel, the application of the differential form of the energy equation, i.e. the backwater equation, enables the prediction of the free-surface profile in the barrel (Appendix B). Its numerical integration predicts the entire free-surface profile in the barrel, in particular the water depth d_{entry} at the entrance of the culvert barrel.

At the entrance of the barrel in a multi-cell structure, the flow cross-section is partially obstructed by the dividing walls between adjacent cells and the total wall thickness must be taken into account into the final design (CHANSON 2004, p. 469). The flow at the barrel entrance may be analysed as a smooth and short transition using the Bernoulli principle:

$$d_{in} + \frac{V_{in}^{2}}{2 \times g} + z_o = d_{entry} + \frac{V_{entry}^{2}}{2 \times g} + z_o \qquad \text{(C-2)}$$

where the subscript in refers to the downstream end of the inlet and the subscript entry corresponds to the culvert barrel entrance flow conditions. The combination of the Bernoulli equation (Eq. (C-2)) and equation of conservation of mass gives the flow properties at the downstream end of the culvert inlet.

Assuming an inlet with wingwalls ([3]), backwater calculations are performed from the downstream end of the inlet to the inlet lip. Note that the backwater calculations may be performed using the standard step method depth-calculated-from-distance.

[3] A simple inlet geometry consists of 45° straight wingwalls.

Upstream of the inlet, the flow transition from the upstream flood plain to the start of the inlet may be analysed using the Bernoulli principle. While the cross-section may be assumed rectangular at the inlet lip (in first approximation), the upstream flood plain is a natural channel and its properties must be used to estimate the flow cross-section area. The results give the water depth and total head in the upstream flood plain at less-than-design flow. In turn, the corresponding afflux may be calculated.

C.3 DISCUSSION

The above method describes one-dimensional calculations of the entire culvert flow for less-than-design conditions, assuming a mild slope, in absence of hydraulic jump in the outlet and immediately downstream of the outlet lip, and without obstacle (e.g. debris) in the culvert inlet, barrel and outlet. The less-than-design flow calculations are conducted assuming free-surface flow in the inlet, barrel, and outlet, the flow being assumed to remain subcritical in the barrel and that no hydraulic jump takes place in the outlet.

The complete free-surface profile and total head line at the embankment centreline may show some sharp change in flow properties at the start of the inlet, the transition from inlet to barrel and at the outlet (Fig. C-3). These changes are linked to some rapid local flow transition, e.g. flow contraction, flow expansion. Figure C-3 presents a typical example of less-than-design flow calculations for a multicell box culvert. Note that the hydraulic engineering calculations are performed from downstream to upstream, since the flow is controlled from downstream: i.e., by the tailwater flow conditions.

In the culvert barrel, the application of the differential form of the energy equation enables a prediction of the free-surface profile:

$$\frac{\partial\left(d + \frac{V_{mean}^{2}}{2 \times g}\right)}{\partial x} = S_o - S_f \qquad \text{(C-3)}$$

where S_o is the bed slope ($S_o = \sin\theta$) and S_f is the friction slope defined as:

$$S_f = \frac{f}{D_H} \times \frac{V_{mean}^{2}}{2 \times g} \qquad \text{(C-4)}$$

with f the Darcy-Weisbach friction factor, D_H the hydraulic diameter: $D_H = 4 \times A/P_w$, A the flow cross-section area, P_w the wetted perimeter, V_{mean} the cross-sectional averaged velocity or bulk velocity, and g the gravity acceleration (HENDERSON 1966, MONTES 1966, CHANSON 2004). The barrel flow calculations are typically undertaken for smooth boundaries and friction factor calculations are discussed in Appendix B. In presence of rough barrel walls or culvert barrel baffles, the flow resistance estimates must be derived from detailed hydrodynamic calculations validated by solid engineering data.

For the culvert barrel flow calculations, great attention must be paid to the wetted perimeter estimates in a multi-cell structure. At the entrance of the barrel in a multi-cell structure, the flow cross-section is obstructed by the dividing walls and the transition between the end of inlet to the barrel entrance may be analysed using the Bernoulli principle.

At the entrance of the inlet (i.e. inlet lip), the flow undergoes a contraction. The transition from the upstream flood plain to the start of the inlet may be analysed using the Bernoulli principle.

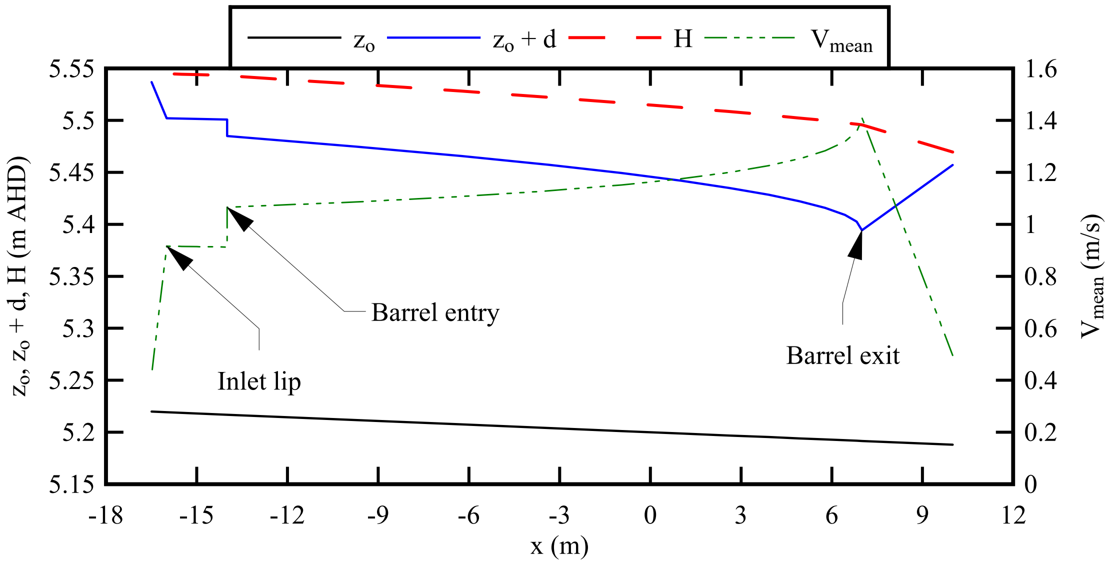


Fig. C-3 - Typical example of longitudinal profile of water depth, mean flow velocity and total head in a multicell box culvert operating at less-than-design flow with subcritical free-surface flow - Q_{des} = 4.8 m^3/s, S_o = 0.0012, 7 cells, Barrel length: 14 m, B_{cell} = 1.00 m, D_{cell} = 0.500 m, Q = 1.3 m^3/s, d_{tw} = 0.21 m

APPENDIX D - SENSITIVITY ANALYSES FOR HYDRAULIC ENGINEERING CALCULATIONS OF FISH-FRIENDLY BOX CULVERTS

D.1 PRESENTATION

Current hydraulic engineering design guidelines of box culverts have been developed for design flow conditions and do not encompass less-than-design flow conditions ($Q < Q_{des}$). Yet fish swim as soon as the water discharge is non-zero: $Q > 0$ and new design guidelines for fish-friendly box culverts are critically needed. Herein, novel engineering design guidelines are considered, based upon two basic concepts:

(a) The culvert design is optimised for fish passage for $Q_{min} < Q < Q_1$; and it is optimised in terms of flood capacity for $Q_1 < Q < Q_{des}$.

(b) Since small-body fish swim next to the channel corners and sidewalls, the swimming performance data are related to a proportion (i.e. percentage) of the wetted flow area where:

$$0 < V_x < U_{fish} \quad \text{(D-1)}$$

with V_x the local time-averaged longitudinal velocity component and U_{fish} a characteristic speed of targeted fish specie.

A very-novel approach is the provision of a minimum relative flow area where the longitudinal water velocity is less than a characteristic fish speed (Eq. (D-1)). The justification is based upon two earlier findings: (1) the rate of work and energy required by fish to thrust itself against the flow is proportional to the cube of the local fluid velocity V_x (WANG and CHANSON 2018), and (2) small-body Australian fish swim next to rectangular channel corners and sidewalls (WANG et al. 2016a, CABONCE et al. 2017, GOODRICH et al. 2018).

The proposed method needs to be sound, simple, economically acceptable and meet engineering standards. Two practical questions are tested herein: what are the influence of the relative threshold Q_1/Q_{des} and of the percentage of flow area on the size and cost of standard box culvert structures?

D.2 METHODOLOGY

A sensitivity analysis was conducted for two multicell box culvert structures, typical of two-lane roadway projects (Table D-1). The characteristics of these structures are detailed in Table D-1. One structure (Culvert 1) was based upon a real site in north-eastern New South Wales. Both structures were equipped with a smooth barrel. Natural tailwater conditions were used: i.e., river gauge data (Culvert 1) (Fig. D-1) and uniform equilibrium flow conditions (Culvert 2).

The original culvert barrel size was calculated to achieve the smallest barrel size with inlet control for the design flow rate Q_{des} and maximum acceptable afflux h_{max}, with the culvert barrel invert at natural ground level (Section 2). The calculation output was the number of cells $(N_{cell})_{des}$, listed in

Table D-1 (14th row).

For less-than-design flow conditions, hydraulic engineering calculations were based upon one-dimensional calculations, using complete calculations (Appendix C) and numerical modelling ([1]). Both methods were tested and validated against the physical model of a single-cell box culvert (described in WANG et al. 2018).

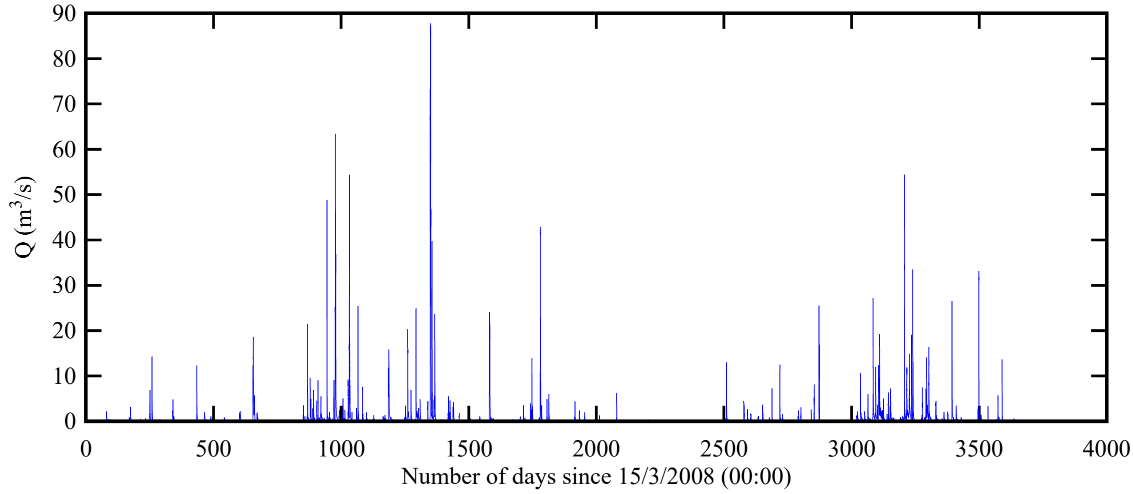
In addition and for Culvert 1, two-dimensional (2D) and three-dimensional (3D) computational fluid dynamics (CFD) calculations were undertaken using the software ANSYS Fluent Version 18.0. The focus of these calculations was to test a lower invert, allowing to retain a 0.3 m deep pool of water in the culvert barrel during dry to very-low flow conditions. The calculations were conducted for one cell only, denoted Culvert 1b in Table D-1.

Table D-1 - Characteristics of multicell box culvert structures

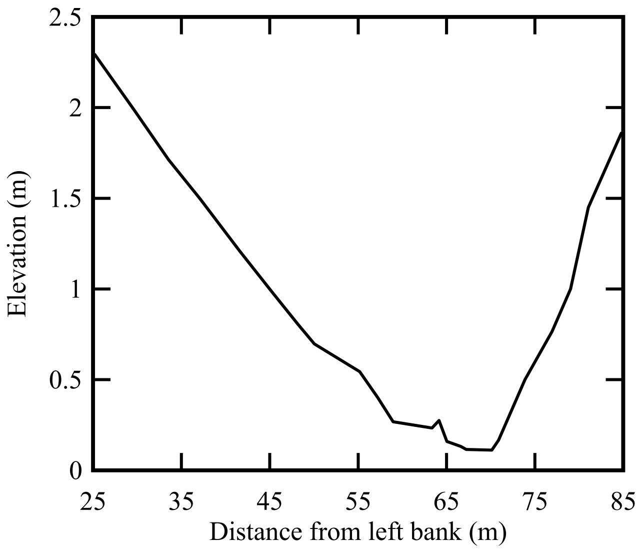
	Culvert 1	Culvert 1b	Culvert 2
Hydrology	Gara River NSW	Gara River NSW	
Tailwater conditions	Gauge data	Gauge data	Uniform equilibrium flow
S_o	0	0	0.012
Design event	1-in-1 year event (2008-2018)	1-in-1 year event (2008-2018)	
Q_{des} (m^3/s)	20.0	--	4.8
Q_{des} (ML/day)	1,728	--	415
q_{des} (m^2/s)	1.92	1.92	0.78
L_{barrel} (m)	8	8	14
D_{cell} (m)	1.0	1.3	0.5
B_{cell} (m)	1.3	1.0	1.0
Boundary roughness	smooth concrete	smooth concrete	smooth concrete
Barrel invert	natural ground level	0.3 m below natural ground level	natural ground level
Maximum acceptable afflux h_{max} (m)	0.55	0.55	0.20
Number of cells $(N_{cell})_{des}$	8 ([1])	1	7 ([1])
$(V_{mean})_{des}$ (m/s)	2.7	1.9	2.0

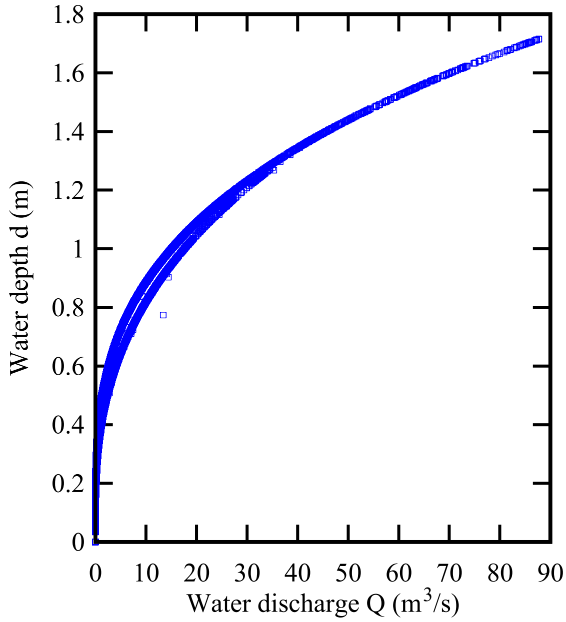
Note: ([1]) Minimum cross-section area for inlet control operation at design flow conditions.

[1] Numerical modelling was conducted with the software HydroCulv version 1.2. (See more information in CHANSON (2004, pp. 508-511).) The entrance and exit loss coefficients were assumed to be 0.5 and 1 respectively. Flow resistance in the barrel was calculated assuming a Darcy-Weisbach friction factor of 0.015.



(A) Hydrograph of the Gara River from 15 March 2008 to 15 March 2018





(B) Channel cross-section on 4 Feb. 1997 (C) Relationship between water depth and discharge

Fig. D-1 - Characteristics of the Gara River at Willow Glen north-eastern New South Wales (Data courtesy of NSW DPI Office of Water) - Catchment area: 121 km^2, site 20635

Discussion

In a box culvert barrel, there is a range of fluid velocities, ranging from zero at the boundaries (i.e. no slip condition) to the cross-sectional maximum water velocity, which is greater than the bulk velocity $V_{mean} = Q/(B \times d)$, with Q the discharge, B the internal width and d the water depth. Physical and numerical modelling of culvert barrel flow deliver a detailed flow map, including a fine characterisation of low-velocity zones (LVZs) (WANG et al. 2016b, CABONCE et al. 2017, ZHANG and CHANSON 2018). In a smooth box culvert channel, the low velocity zones extend around the wetted perimeter and are particularly sizeable next to the bottom corners. These low velocity regions are preferential swimming zones for fish as shown by LUPANDIN (2005) and COTEL et al. (2006), and more specifically for small-body Australian native fish by WANG et al. (2016a) and CABONCE et al. (2017).

Detailed velocity measurements were conducted in a 12 m long 0.5 m wide smooth rectangular, based upon 300 measurement points for a range of subcritical turbulent flow conditions with a fine spatial and temporal resolution. The results are summarised in Figure D-2, showing the percentage of flow area where the time-averaged longitudinal velocity V_x was less than a percentage of the bulk velocity. For example, Figure D-2 indicates that 30% of flow area corresponded to a low-velocity zone with longitudinal velocity $0 < V_x < 0.75 \times V_{mean}$. The results are used herein.

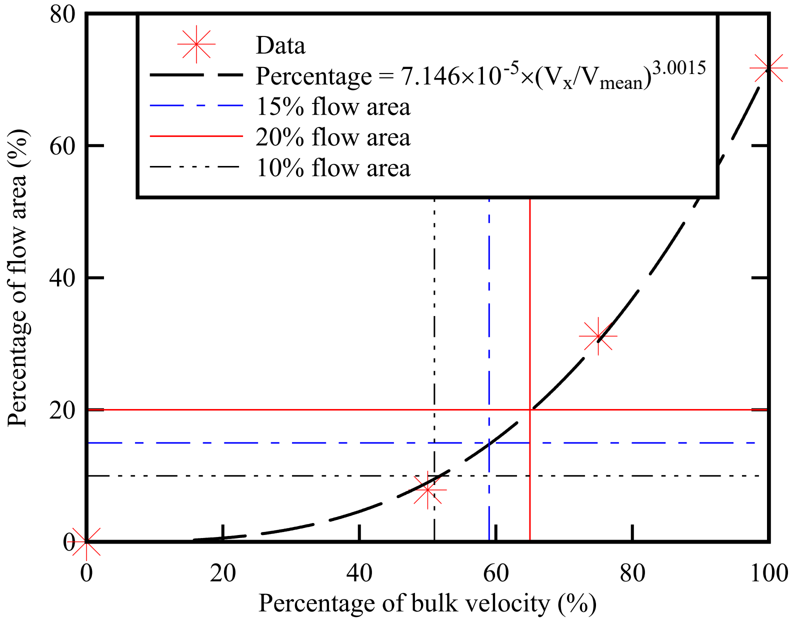


Fig. D-2 - Relationship between percentage of flow area and relative longitudinal velocity V_x/V_{mean} in smooth rectangular channel with aspect ratio: $3 < B/d < 5.2$ - Data set: CABONCE et al. (2017), $Q = 0.026$ & $0.056\ m^3/s$, $B = 0.5$ m

D.3 RESULTS

D.3.1 Basic results - Culverts 1 and 2

Hydraulic engineering calculations were performed for a range of less-than-design discharges $0.1 < Q/Q_{des} < 0.5$. The tailwater conditions were subcritical and the culvert flow remained subcritical with outlet control. Characteristic fish speeds were considered from $0.2 < U_{fish} < 1$ m/s based upon the targeted fish specie (GORDOS, M. 2018, *Person. Com.*). Percentages of flow area corresponding to low-velocity zones were tested between 10% and 20%.

The results are reported in Figure D-3, showing the increase in number of culvert barrel cells to achieve the expected low-velocity zone, i.e. a percentage of flow area where $0 < V_x < U_{fish}$. In Figure D-3, the left graphs correspond to the Culvert 1 and the right graphs are for the Culvert 2 (Table D-1). For each graph, the lower horizontal axis is the dimensionless number of cells $N_{cell}/(N_{cell})_{des}$, where N_{cell} is the number of barrel cells for the fish-friendly culvert design and $(N_{cell})_{des}$ is the number of barrel cells for optimum flood capacity design ([2]). The upper horizontal axis is the relative increase in number of barrel cells compared to the optimum flood capacity design, i.e. $(N_{cell}-(N_{cell})_{des})/(N_{cell})_{des}$. In first approximation, the increase in barrel cell number would correspond to the increase in culvert construction costs to achieve fish passage, in the form of additional precast cell units, although, depending upon the site, the final design might requires construction of a second structure in an anabranch or selection of a bridge structure instead of a culvert, all at a greater cost.

As an example, let us consider Figure D-3C(Left). For $Q_1/Q_{des} = 20\%$, and an expected low-velocity zone corresponding to 20% percentage of flow area where $0 < V_x < U_{fish} = 0.2$ m/s, the increase in number of barrel cells would be 180%, or $N_{cell}/(N_{cell})_{des} = 2.8$.

Overall the findings (Fig. D-3) demonstrate qualitatively and quantitatively that the cost of a box culvert increases with decreasing characteristic fish speed U_{fish}, increasing discharge threshold Q_1/Q_{des} and increasing percentage of flow area:

$$\text{Culvert Cost} \uparrow \equiv U_{fish} \downarrow + \; Q_1/Q_{des} \uparrow + \; \%\text{flow area} \uparrow \qquad \text{(D-2)}$$

More specifically, the quantitative results show the critical impact of characteristic speed U_{fish} of target fish specie. It is prohibitive to design smooth box culverts for characteristic swimming speeds less than 0.3 m/s, within the range of investigated flow and boundary conditions. Conversely, a targeted fish speed $U_{fish} > 0.7$ m/s is readily achieved for $Q < 0.5 \times Q_{des}$.

Another key parameter is the discharge threshold Q_1/Q_{des}. The provision of fish passage capability for $Q > 0.5 \times Q_{des}$ is prohibitive. The selection of $Q_1/Q_{des} < 30\%$ tends to be achievable for more moderate increase in costs (Fig. D-3B to D-3D).

Finally the relative size of the low-velocity zone impacts also on the structure costs. Based upon detailed physical modelling with flow boundary conditions for which fish endurance was tested, 15% of flow area with $0 < V_x < U_{fish}$ may be an appropriate target (WANG et al. 2016b, CABONCE et al. 2017).

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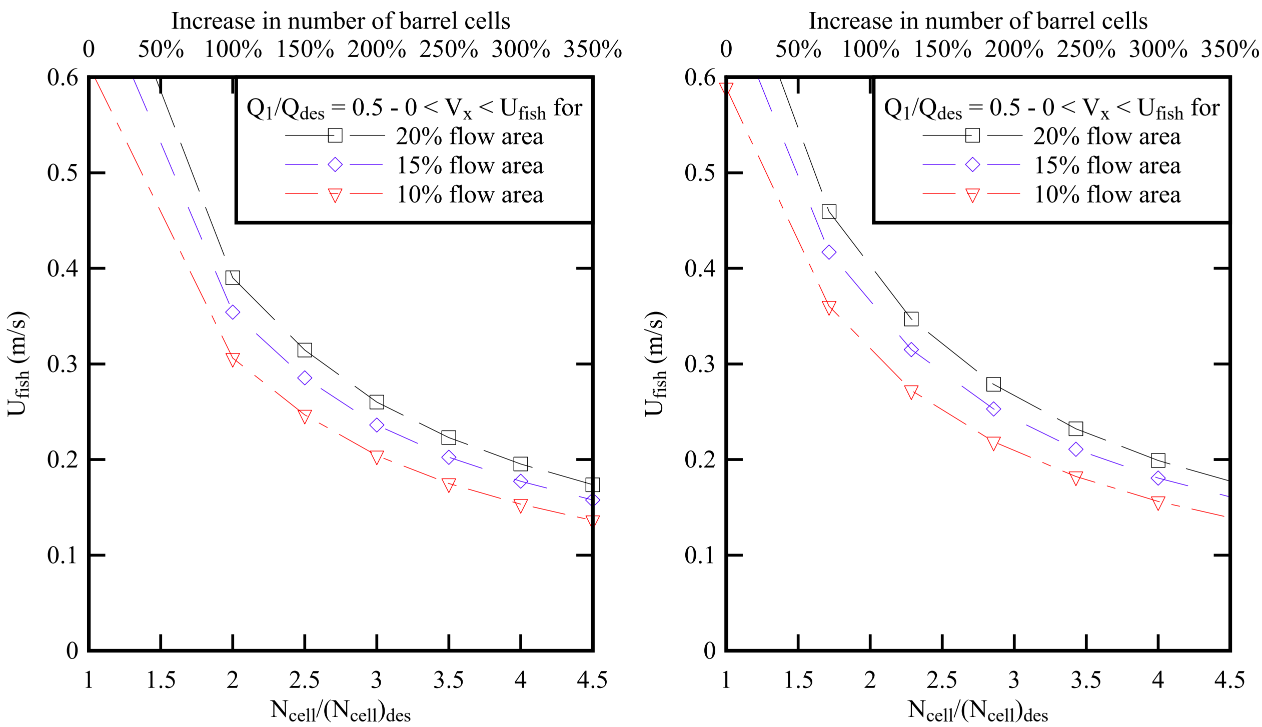
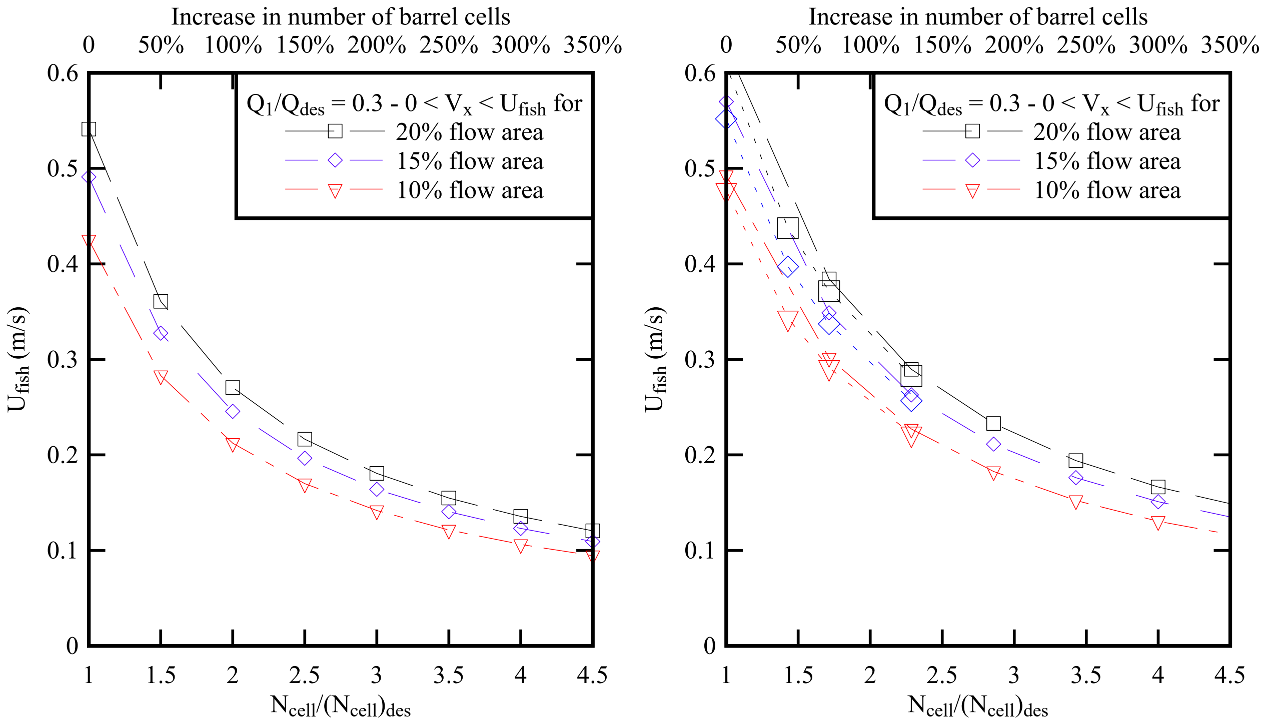
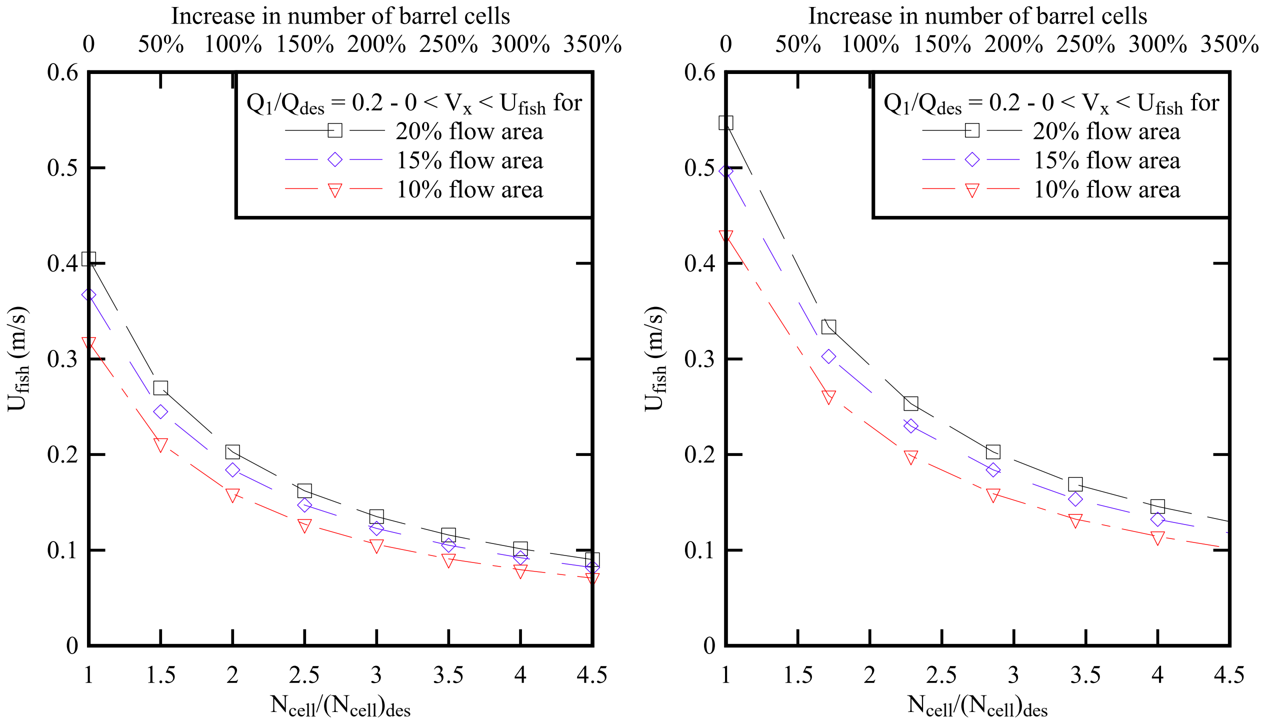
[2] That is, the minimum number of precast barrel cells for inlet control operation at design flow conditions (Table D-1).



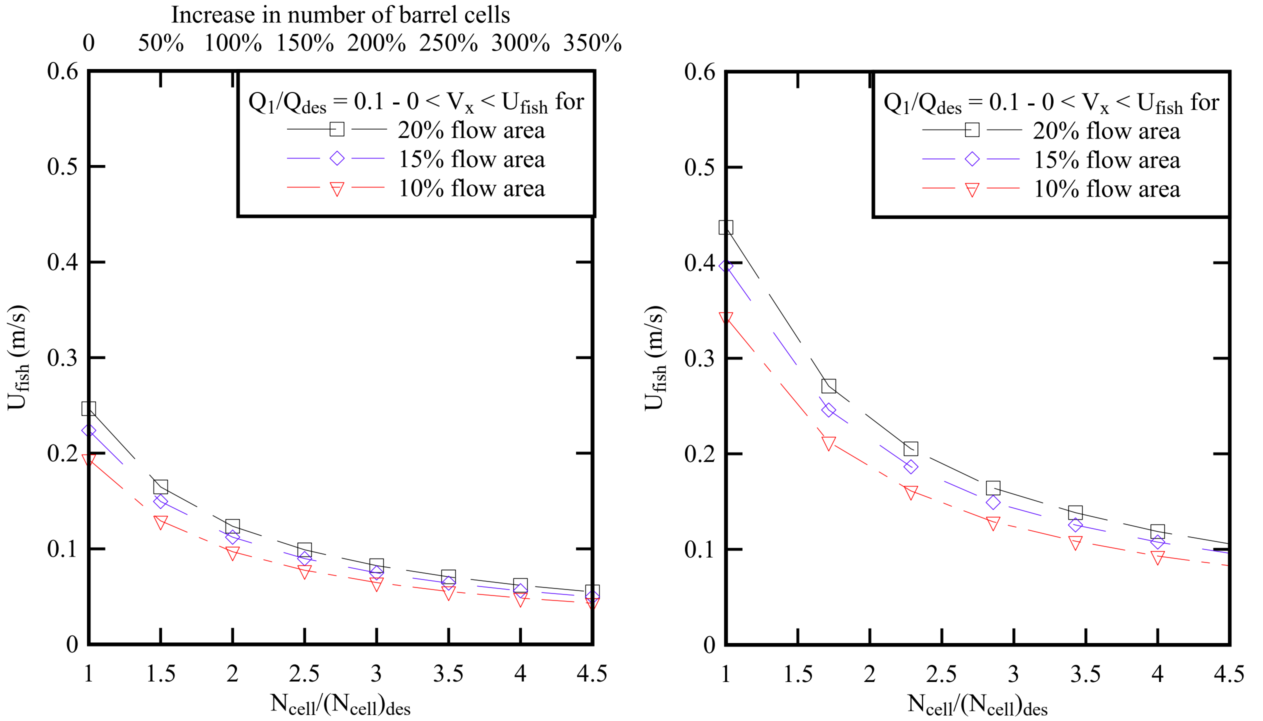
(A) Q_1/Q_{des} = 50% - Culvert 1 (Left, Gara River) and Culvert 2 (Right)



(B) Q_1/Q_{des} = 30% - Culvert 1 (Left, Gara River) and Culvert 2 (Right)



(C) Q_1/Q_{des} = 20% - Culvert 1 (Left, Gara River) and Culvert 2 (Right)



(D) Q_1/Q_{des} = 10% - Culvert 1 (Left, Gara River) and Culvert 2 (Right)

Fig. D-3 - Increase in number of cells for fish-friendly multicell box culverts as a function of the threshold discharge Q_1/Q_{des}, percentage of flow area where $0 < V_x < U_{fish}$ and characteristic fish performance U_{fish} - Culvert 1 (Left, Gara River) and Culvert 2 (Right)

D.3.2 Detailed results - Culvert 1b

Detailed calculations were conducted for a culvert barrel invert installed 0.3 m below the natural ground level (Fig. D-4). The recessed barrel barrel invert configuration was based upon current Australian guideline recommendations (FAIRFULL and WHITRIDGE 2003). A definition sketch is shown in Figure D-4. CFD calculations were performed for q/q_{des} = 1, 0.3, 0.2 and 0.1, where q is the unit discharge and q_{des} is the design unit discharge (Table D-1). The results are presented in Figure D-5, in terms of longitudinal velocity contours at several culvert barrel cross-sections. Table D-2 summarises quantitative results in terms of percentage of flow area where $0 < V_x < U_{fish}$.

For q/q_{des} = 10% (Q_{cell} = 0.192 m^3/s), 80% of flow area is associated with a time-averaged longitudinal velocity V_x less than 0.3 m/s. With increasing flow rate, the percentage of flow area with $0 < V_x < 0.3$ m/s decreased, as seen in Table D-2.

If the test case q/q_{des} =10% is deemed to satisfy fish passage requirements and used as the reference, the number of required barrel cells $N_{cell}/(N_{cell})_{des}$ would be 1.95 and 3.2 for q/q_{des} = 20% and 30% respectively.

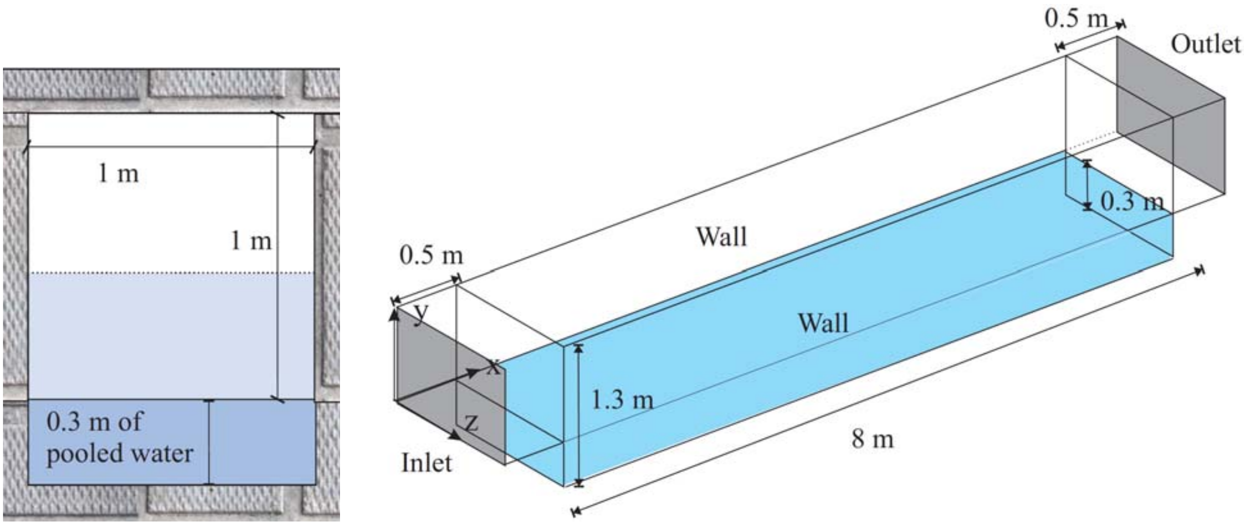
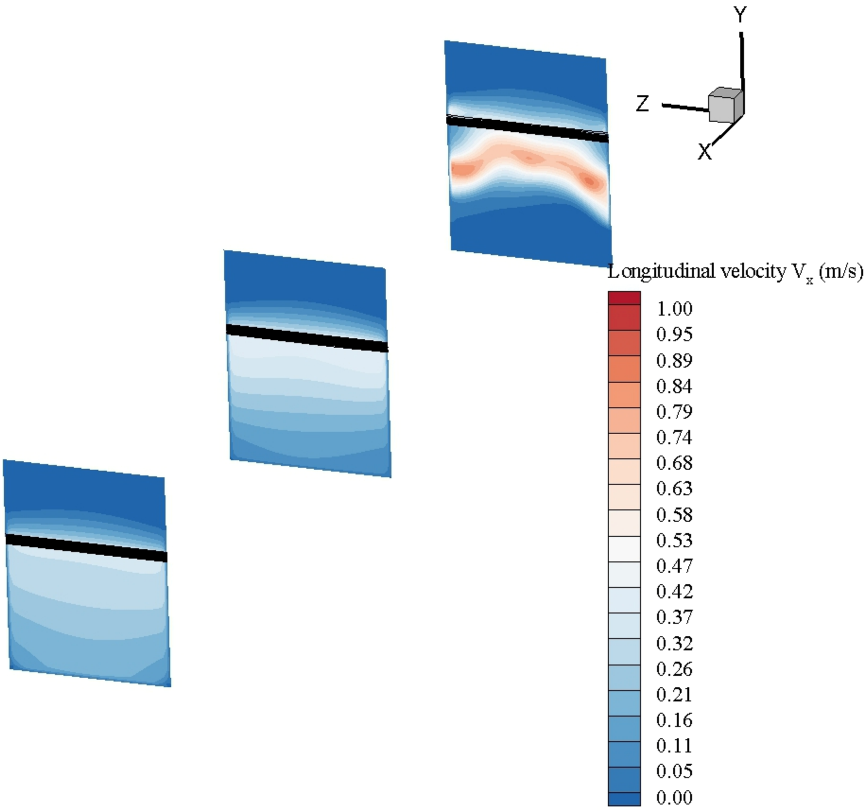
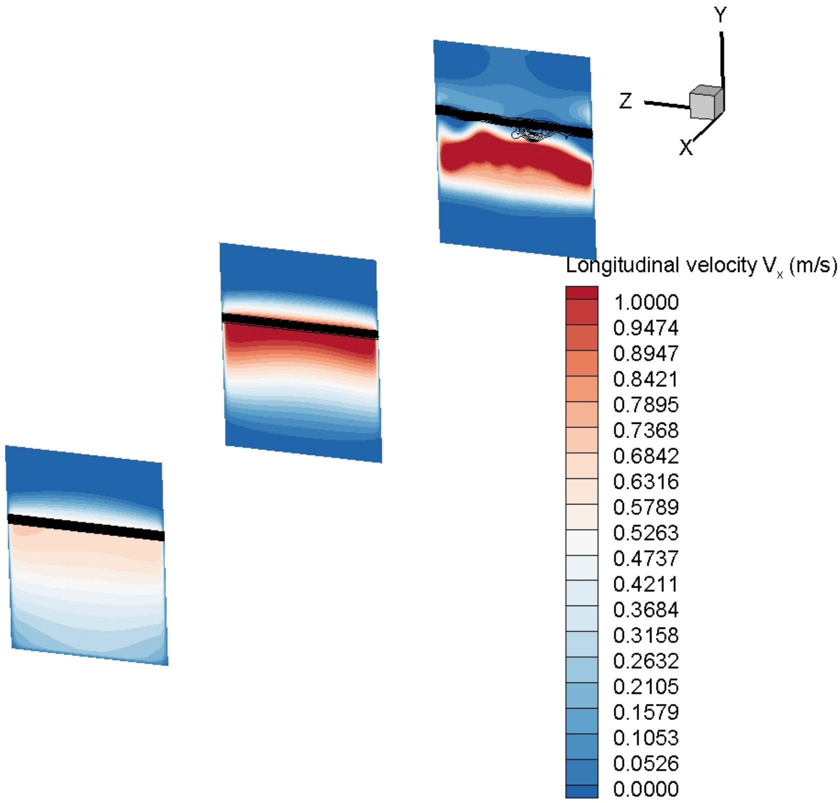


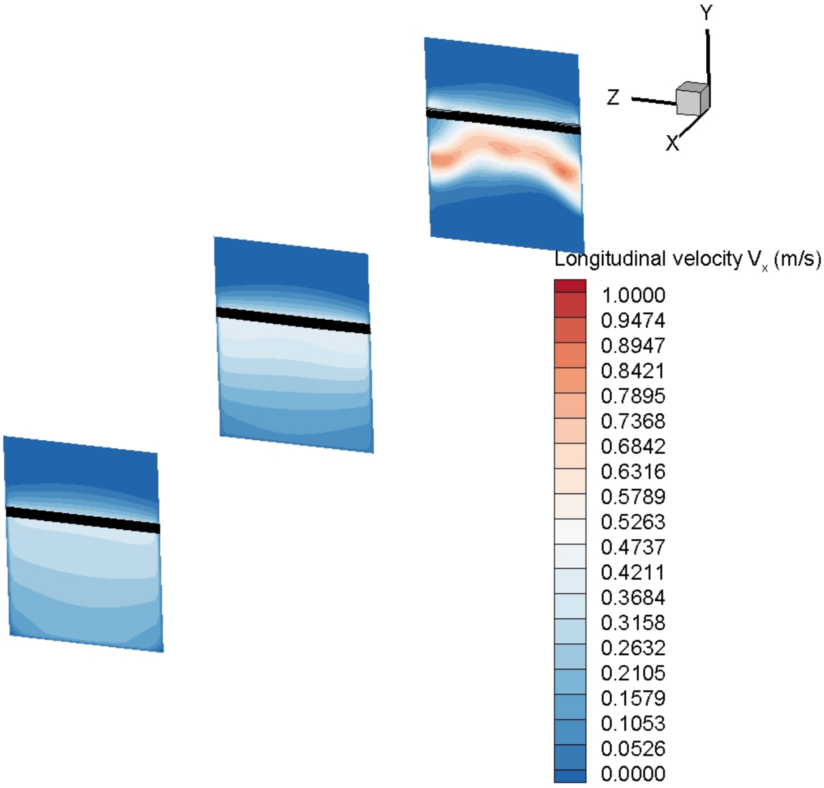
Fig. D-4 - Definition sketch of pooled culvert barrel (Culvert 1b)



(A) q/q_{des} = 30%, Barrel water depth: 0.94 m, V_{mean} = 0.66 m/s



(B) q/q_{des} = 20%, Barrel water depth: 0.83 m, V_{mean} = 0.45 m/s



(C) q/q_{des} = 10%, Barrel water depth: 0.81 m, V_{mean} = 0.24 m/s

Fig. D-5 - Longitudinal velocity contours in the culvert barrel (Culvert 1b) for less-than-design discharges - Black line indicate the free-surface - Flow direction from top right to bottom left

Table D-2 - Percentage of flow area where $0 < V_x < U_{fish}$ in Culvert 1b

			U_{fish} (m/s)			
q/q_{des}	d (m)	V_{mean} (m/s)	0.2	0.3	0.4	0.5
10%	0.81	0.24	30%	78%	100%	100%
20%	0.83	0.45	4%	22%	40%	58%
30%	0.94	0.66	8%	22%	31%	40%

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